Implementations of Electric Vehicle System Based on Solar Energy in Singapore

-Assessment of Solar Photovoltaic Systems

by

Li Sun

B.Eng. (Hons), Electrical and Electronic Engineering (2008)

Nanyang Technological University

Submitted to the Department of Materials Science and Engineering
in Partial Fulfillment of the Requirements for the Degree of
Master of Engineering in Materials Science and Engineering
at the
Massachusetts Institute of Technology
September 2009

Signature of Author: ....

Department of Materials Science and Engineering
August 5, 2009

Certified by: ....

Yet-Ming Chiang
Kyocera Professor of Ceramics
Thesis Co-Supervisor

Certified by: ....

Andy Chu
Director, A123 Systems
Thesis Co-Supervisor

Accepted by: ....

Christine Ortiz
Associate Professor of Materials Science and Engineering
Chair, Department Committee on Graduate Students

Implementation of Electric Vehicle System Based on Solar Energy in Singapore

-Assessment of Solar Photovoltaic System

by

Li Sun

Submitted to the Department of Materials Science and Engineering
on August 14th, 2009 in Partial Fulfillment of the
Requirements of the Degree of Master of Engineering in
Materials Science and Engineering

Abstract

To evaluate the feasibility of solar energy based Electric Vehicle Transportation System in Singapore, the state of the art Photovoltaic Systems have been reviewed in this report with a focus on solar cell technologies. Various solar cell technologies were evaluated based on characteristics such as efficiency, reliability and cost to identify a best working one under Singapore's hot and humid climate. Commercial CdTe modules were found to have the best efficiency to cost ratio, making them the best module choice in land-scarce and tropical Singapore. Based on the market price and characteristics of CdTe modules from manufacturer First Solar Ltd, two PV systems based on an apartment model and a private house model were evaluated.

The cost of electricity from a relatively large scale grid-tied PV system is found to be at around US$0.173/kWh which is not market competitive with the utility electricity price of US$0.109/kWh in Singapore. But with enough capital funding and government incentives such as rebate or feed-in price tariff, PV electricity generation could become economically feasible. The small private house system is found not economical as a means of household electricity generation even with current status of government rebate. When carbon trading is considered, the current trading price has to be increased by around 7 times of the current value or 3 times of the predicted price at 2016 to offset the difference with the utility electricity price.

Thesis Co-Supervisor: Yet-Ming Chiang
Title: Kyocera Professor of Ceramics

Thesis Co-Supervisor: Andy Chu
Title: Director, A123 System

Acknowledgement

Here I would like to express my sincere gratitude to my advisors, Professor Yet-Ming Chiang and Dr Andy Chu, without whose advices this project would not have been completed.

I would also like to thank my teammates, Xiaogang Liu, Yaliang Chen and Haitao Fu, for all the fruitful discussion, suggestions, help and collaborations.

Contents

Part 1: Project Introduction

This work documented in this report is a constituent part of the project entitled "Implementation of Electric Vehicle System Based on Solar Energy in Singapore" (referred as *the Project* in this report). This part of the project reported here is to mainly evaluate the economic profitability of large-scale solar photovoltaic (PV) system installations in Singapore, which will further help determine the economic feasibility of solar electricity based Electrical Vehicle (EV) transportation system. This report can also be referred as an independent work on the technological and economical assessment of photovoltaic technologies.

1. Project Background and Objective

1.1 Background of the Project

On July 11 2006, Singapore formally acceded to the Kyoto Protocol as a non-Annex B country. Although Singapore is not obliged to commit to greenhouse gas emission reduction until 2012, it will have to reduce its absolute CO2 emission based on the 1990 benchmark during the second round from 2012 to 2016 [1]. Figure 1 shows the total absolute CO2 emission and the emission intensity in Singapore [2]. It can be seen that the absolute CO2 emission had increased more than 1.84 times from 1990 to 2005, or 21.5 million tons to 39.6 million tons, while the carbon intensity[1] had a slight decrease due to the fast growth in Gross Domestic Product (GDP) in the time span. Therefore, to meet the stipulated requirements as a member of the Kyoto Protocol, reducing the absolute CO2 emission to 1990 level by 2016 is an eminent task to Singapore.

[1] Carbon intensity is defined as the CO_2 emission from the consumption and flaring of fossil fuel (oil, natural gas, coal, etc) per thousand dollars of gross domestic product.

Table 1 [2] illustrates the major contributors of CO2 emission in Singapore. It can be seen that the top three contributors, power generation, industry usage of energy and transport, constitute about 98% of the total CO2 emission in Singapore in 2005.

In order to meet the Kyoto requirement, the Singapore government has initiated a series of acts to reduce CO2 emission in the country which include using highly efficient combined-cycle gas turbine for power generation, replacing crude oil with natural gas as the major source for electricity generation, restricting private car ownership and encouraging people to use public transport system and etc.

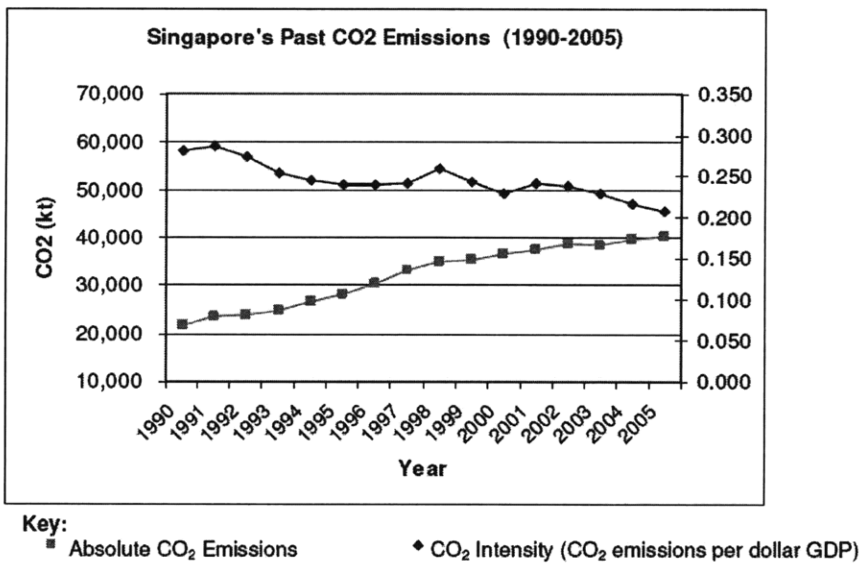


Figure 1: Singapore's CO_2 Absolute and Intensity Emissions 1990-2005

Key CO2 Contributors 2005 Kilo tones

	Electricity Generation	Industry	Transport	Buildings	Consumers/ Households	Others
Primary Consumption use combust fuel	**19,315** (48%)	**13,465** (33%)	**7,056** (17%)	**325** (1%)	**216** (1%)	-
Secondary Consumption use electricity		**8,328** (21%)	**930** (2%)	**5,910** (15%)	**3,415** (8%)	**732** (2%)
Overall		**21,793** (54%)	**7,986** (19%)	**6,235** (16%)	**3,631** (9%)	**732** (2%)

TOTAL CO_2 = 40,377 kilo tonnes

Table 1: CO2 Emission by Sectors in Singapore in 2005

1.2 Objectives of the Project

In this project, we will propose a sustainable transport system based on Electric Vehicles (EV) that runs on solar energy, which could help levitate CO2 emission in the transport sector. The economic feasibility and environmental benefits of this system will be evaluated.

EV refers to the vehicles that are "propelled by electric motors powered by rechargeable battery packs", which includes a series of vehicle types based on their kinds of motors and forms of energy source. BEV (Battery Electric Vehicle) refers to electrical vehicles that have electric motors and run purely on electricity. "plug-in hybrid" EV (PHEV) refers to those Hybrid EVs with both a combustion engine and an electric engine, whose battery can be "recharged by connecting a plug to an electric power source." [4]. "Hybrid EV"(HEV) is the type of EVs that are propelled by a combination of gasoline engines and electric motors[3], but without a battery charging plug. We will call them XEV in sum in this report.

Compared with conventional vehicles running on Internal Combustion Engines (ICE), XEVs have several major advantages including reduction of CO_2 and other exhaust gas emission, higher overall fuel efficiency[3], and potential economic attractiveness[4].

As presently electricity in Singapore is generated from fossil fuel, XEVs running on such type of electricity are not absolutely green vehicles. Thus clean energy resources have to be utilized to make XEV transportation absolutely clean. As a city state located in tropical Southeast Asia, Singapore has abundant solar energy resources as compared to other type of clean energy options. The government is also committed to promote solar industry in the country with funding supports and policy incentives to promote solar industries and solar technologies. For example, in 2007, a total of S$350 million public funding was announced to support the clean energy industry where solar energy is the main focus[5]. The clean energy program office (CEPO) set up by the government also launched a S$17 million Clean Energy Research and Test-bedding Program (CERT) in April 2007 to provide opportunities for government agencies to collaborate with private companies to develop and testbed clean energy applications and solutions[6]. In 2008, CEPO also launched a Solar Capability Scheme, offering a 30% to 40% offset towards the total capital cost of building integrated solar systems[7].

Under such a political environment, potential of solar energy as an electricity generation source will be evaluated. It will cover solar thermal systems and solar photovoltaic (PV) systems.

In this group project, the four of us – Yaliang Chen, Xiaogang Liu, Haitao Fu, and I – will evaluate the feasibility of introducing this XEV model into Singapore based on solar energy as the source of electricity generation. Our tasks will encompass independent technical and market assessment of the key technologies involved in this model. Moreover, we will construct an integrated XEV implementation model as a group.

A detailed market and policy review for the energy sector and transportation sector was presented as the group's collaborative work in one separate report titled as "Market and Policy Review of the Energy Sector and the Transportation Sector in Singapore".

Individually, Liu will be examining solar thermal systems for electricity generation; I will look at solar photovoltaic (PV) systems for electricity generation; Fu will focus on the battery technologies for XEV; Chen will evaluate flow batteries as the energy storage solution for electricity generated from solar panels. The individual work can be found in our respective thesis report for references.

Based on the reviews of Electric Vehicles (EVs), Solar Thermal and Solar PV Systems, and Flow Battery Storage, we as a group will be investigating the feasibility of implementing EV transportation system based on solar electricity. Four different models will be built and evaluated, namely the Battery Swapping Model, the PHEV Private Car Model, the standalone Carpark PV System Charging Model with Energy Storage and the Grid-tied PV-EV System model.

1.3 Objective of the Thesis

As a city state in tropical southeast Asia with a latitude of 1.32°N[8], Singapore's daily solar irradiation does not change much throughout a year with an average of 4.35kWh/m2 and a maximum variation of 1kWh/m2[9], which are higher than that in Germany and Japan where PV technologies have found wide applications. In terms of diffusive and direct irradiation division, solar irradiation in Singapore has a diffusive component that is slightly higher than 40%[9]. For

Central Europe where Germany is located, the solar irradiation has a diffusive component of about 50%[10, 11]. Thus Singapore is considered to have a high potential for PV applications.

In this report, a general technology overview on the different components of PV systems will be carried out with a focus on solar cell technologies. Various market available and laboratory technologies will be evaluated based on Singapore's climate condition. The best performance module currently in market will be selected based on the evaluation and used to carry out the analysis of PV system in Singapore.

To evaluate the economic feasibility of solar PV systems in Singapore, grid-connected and standalone PV system will be considered based on practical limitations. The cost of solar electricity from PV systems will be calculated and compared with the current utility electricity prices. Based on the comparisons, the necessity of government incentives will be determined and corresponding government policies will be suggested in order to promote PV system in Singapore.

Part 2: Assessment of Solar Photovoltaic Systems

1. Introduction

In recent years, there has been a global call for renewable energy development due to the climate change and depletion of fossil fuels. According to the United States Energy Information Administration (EIA)[12], world energy consumption has increased more than 80% since 1980. With most of the energy generated from non-renewable fossil fuels, increasing energy consumption has resulted in an increase rate of 2.1 percent per year in carbon dioxide emission, which has caused a faster global temperature increase, and a faster depletion of fossil fuel resources, as shown in Figure 2[13].

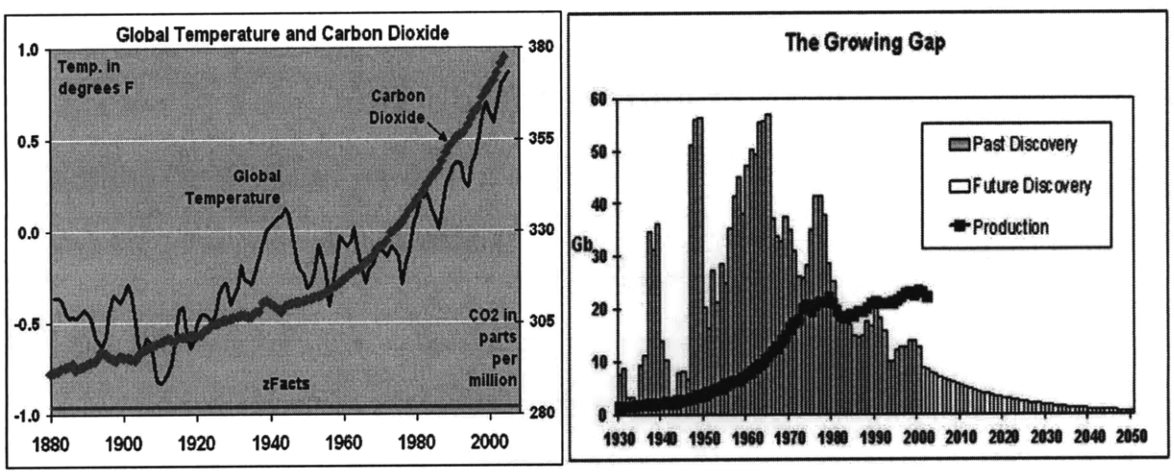


Figure 2: Global Carbon Dioxide Emission and Fossil Fuel Production Trend

With these imminent problems in front, renewable energy development has been strongly focused by governments. Among various type of renewable energy, solar energy is the most widely available renewable source that is generally harvested in the form of heat or electricity. In terms of electricity generation, two types of methods are available, namely Concentrated Solar Power (CSP) and Solar Photovoltaic (PV). CSP or solar thermal energy utilizes concentrated light to produce steam which then drives a conventional power plant while solar PV directly turns light into electricity through the photoelectric effect. In terms of deployment, CSP concentrators are mostly used in large quantities to build power plants while PVs are more flexible which besides concentrated plants can also be integrated into roofs, building facades, or any available sun-illuminated surfaces.

In the past decade, world PV market has been growing exponentially at a compounding rate of 33%, and this growth rate is expected to sustain in the next decades to come. In 2008, the global PV market has more than doubled than that in 2007 and the accumulated installed PV power till 2008 has reached 14.7GW[14]. At the same time, the cost of solar panels in terms of dollars per watt-peak has been continuously decreasing[15]. The plot in Figure 3 demonstrates this trend of production increase and module cost reduction.

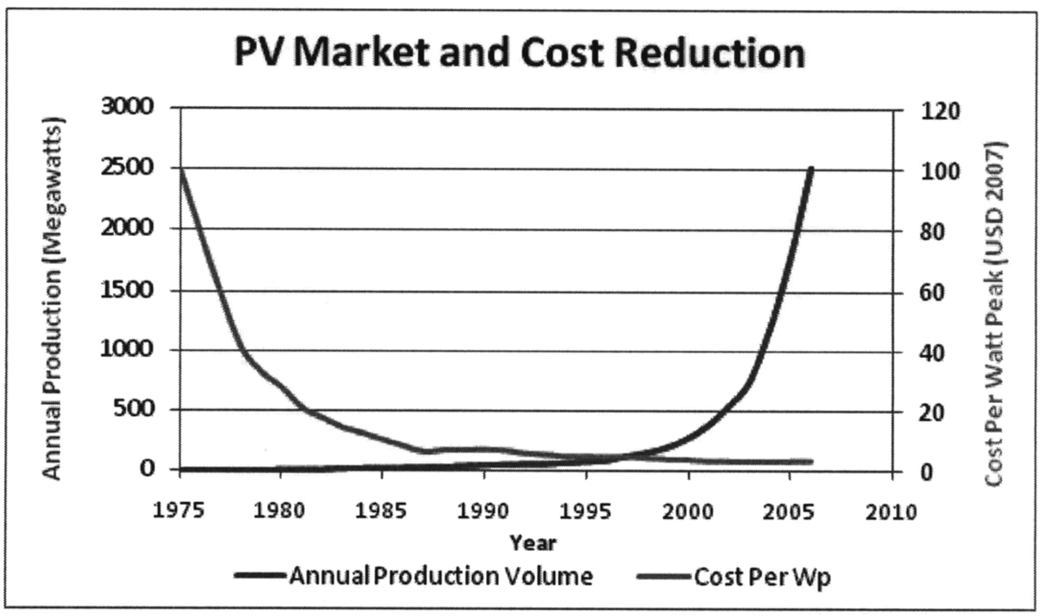


Figure 3: Production Volume Increase and Cost Reduction Trend for PV

In the specific context of Singapore, solar energy has the greatest potential to serve as the clean energy source due to its abundance, government support and continuous worldwide technology advancement. With the objective of integrating photovoltaic systems with XEVs, the following report is going to evaluate the cost and benefits of installing such a PV system for solar electricity generation which could serve as a clean energy source to support XEV transportation.

In the first section, a review will be carried out for the current in-market and in-lab solar cell technologies, which will help identify a best type of in-market PV modules and a best in-lab solar cell technology for subsequent cost evaluation. Then a cost model which parameterizes major attributes of a solar PV system will be built to carry out the evaluations. With such a model, practical evaluations with the integrated XEV system will be done with the rest group members.

2. Solar Irradiation in Singapore

2.1 Solar Energy from the Sun

Considering the Sun as a blackbody at a temperature close to 5800K, the average energy influx incident on a unit area perpendicular to the sunbeam outside the earth atmosphere is called Solar Constant S, which can be calculated as $1367W/m^2$ based on black body radiation with the knowledge of the sun radius and Sun-Earth distance[10]. To derive the solar radiation incident on the earth surface, the atmospheric scattering and absorption effect have to be taken into account. This effect is calibrated as the relative length of the direct sunbeam path through the atmosphere, termed as Air Mass (AM), which brings an exponential attenuation to the extraterrestrial radiation[16]. For extraterrestrial spectrum, AM is 0 (short as AM0), while the radiation from the Sun at zenith on a clear summer day at sea level corresponds to an AM of 1(short as AM1). AM1.5 is a typical global solar spectrum with a corresponding total irradiance of $1kW/m^2$, which is termed as "one sun irradiance" and serves as a standard to test solar cells and modules[10]. Thus the solar energy received by a particular spot on the earth highly depends on its relative position with the sun and local atmospheric conditions. The integrated value of solar irradiance over time is called solar irradiation, and the daily solar irradiation is of particular interest in the design of PV systems[10]. Solar irradiation measured for a panel positioned horizontally relative to the earth surface is called horizontal solar irradiation which serves as an international standard to compare solar irradiations at different latitudes. In practice, the panels are often fixed at a particular angle due to inclination of the rooftop as well vertical positioning of building facades and windows. At places where no restriction is applied on the tilting angle, an angle of tilt is preferred for standalone systems at a particular location to both maximize direct solar irradiation and moderate the distribution of irradiation over summer-winter seasons. For grid-tied systems, an angle is sometimes preferred just to maximize direct solar irradiation[11].

2.2 Solar Irradiation in Singapore

As a city state in tropical southeast Asia with a latitude of 1.32°N[8], Singapore's daily solar irradiation does not change much throughout a year with a maximum variation of around 1kWh/m^2[9]. This value is smaller as compared to the summer-winter irradiation variation in Europe, Northern America and Japan which are located at higher latitudes but where large scale PV installation is found.

Figure 4 and Figure 5 shows the plot of monthly average daily horizontal irradiation over a period of 15-30 years in Singapore, Freiburg, Osaka and Los Angeles, where we can found a typical climate suitable for PV installation corresponding to the above respective countries[17, 18]. As demonstrated in the plot, Singapore has a well distributed solar irradiation. The year-round average with a value of 4.35kWh/m2 (equivalent to 4.35 Peak Solar Hours[2]), though slightly lower than that in California (4.9 kWh/m2), is close to 1 kWh/m2 or 30% higher than that in Germany (3.02 kWh/m^2) and Japan (3.10 kWh/m^2).

[2] Peak Solar Hour = 1kWh/m^2

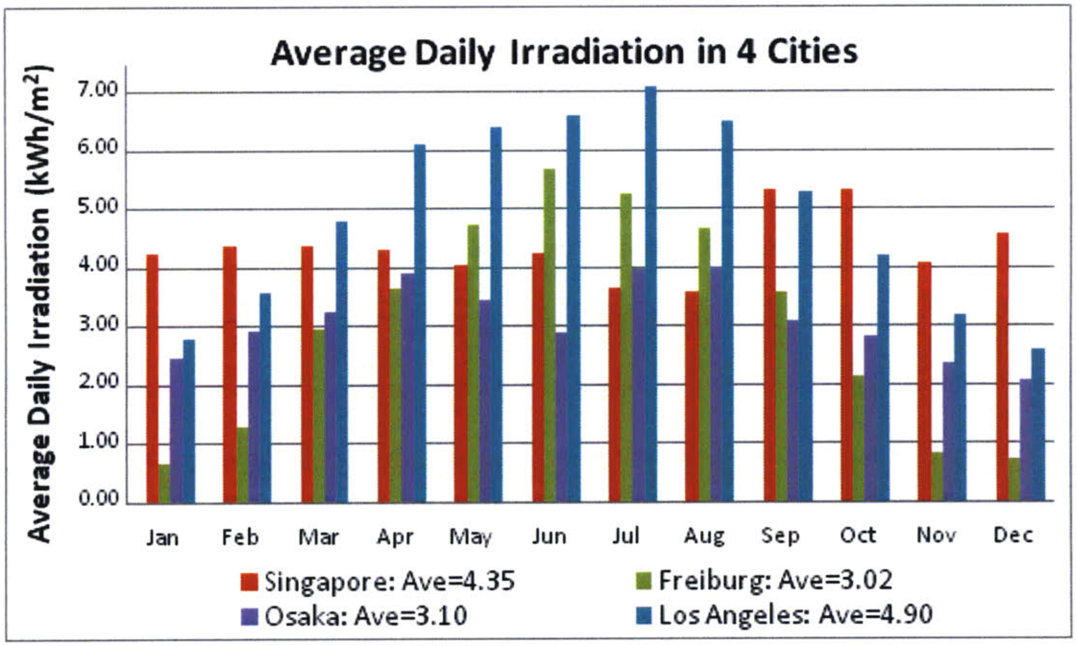


Figure 4: Detailed Average Daily Irradiation in 15-30 Years in Singapore, Freiburg, Osaka and Los Angeles

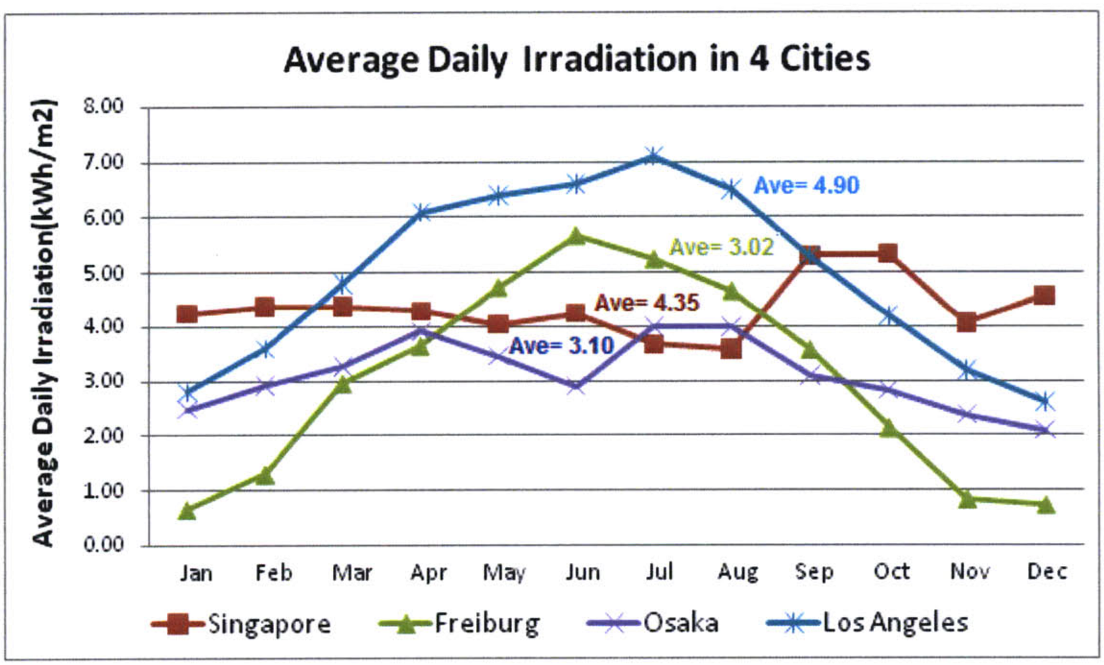


Figure 5: Average Daily Irradiation in Singapore, Freiburg, Osaka and Los Angeles

Peak power irradiance profile with a 15° panel tilt (for best performance) is shown in Figure 6 where the solar irradiation measured on a typical cloudy day, a typical intermittent cloudy-sunny and a typical sunny day during March and April of 2004 was plotted[19]. For a typical sunny day in Singapore, there are 3 hours from 12:00pm to 15:00pm when the solar irradiance is above $1000W/m^2$ and 5 hours from 10:20am to 15:20pm when the solar irradiance is above $800W/m^2$.

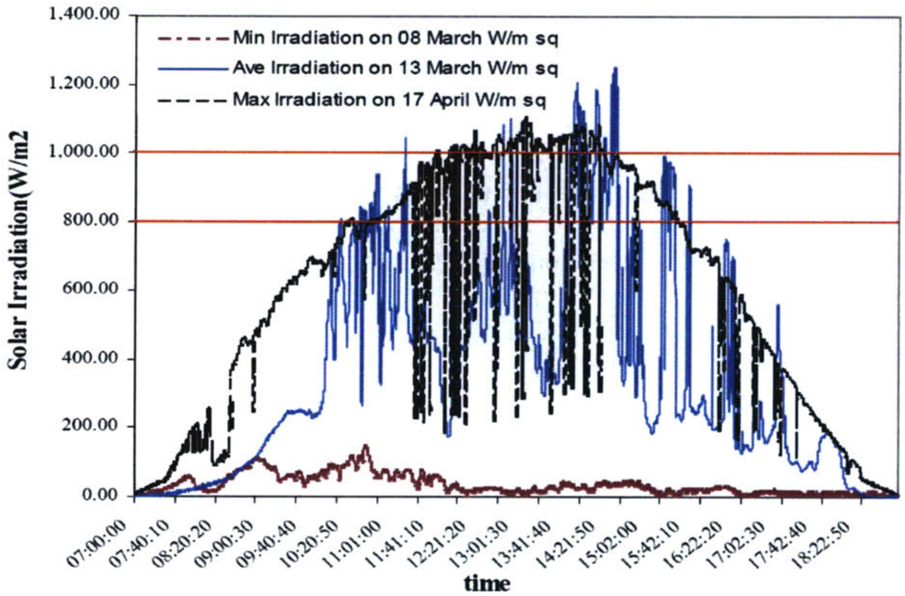


Figure 6: Solar Irradiance on three typical days in Singapore

In terms of the direct and diffusive components, it has been shown that Singapore's solar irradiation has a diffusive component that is slightly higher than 40%[9]. For Central Europe where Germany is located, the solar irradiation has a diffusive component of about 50%[10, 11]. In Southern Europe and North America where the weather is dry and sunny days are common, the diffusive component of solar irradiation is around 30%[10].

It was also mentioned in Chapter 3 of Part 1 that Singapore's well distributed solar irradiance enables the size reduction of battery storage in a standalone PV system, which is advantageous in decreasing the cost of non-grid-tied PV systems. With an average value above $4.0kWh/m^2$ at the 15° degree tilt condition, the daily solar irradiation in Singapore is still above $3kWh/m^2$ after a typical 2% solar cell efficiency degradation due to an elevated temperature for roof top panels in Singapore[19]. In terms of the direct and diffusive irradiation combination, Singapore has a higher direct irradiation component than a typical situation in Germany. Though the diffusive part will yield a lower operating efficiency for the panels designed for direct irradiance, it is especially useful for Building Integrated Photovoltaic (BIPV) applications. Thus in sum, Singapore can be a good candidate to harvest solar energy with PV systems.

In the following evaluation of PV systems for electricity generation, the daily solar irradiation of $4.0kWh/m^2$ will be used and the peak irradiance will be taken from Figure 6.

3. PV Industry Supply Chain and Solar PV Systems

3.1 PV Industry Supply Chain

The PV industry supply chain is illustrated in Figure 7. Solar cells directly manufactured from raw materials are the smallest units in a PV system. Solar cellars are then connected in series (and/or parallel) to form modules with the protection of auxiliary structures, where the number of solar cells in a module depends on the subsystem compatibility requirement. Modules are sold by manufacturers to retailers who will handle the sales and installation of PV modules.

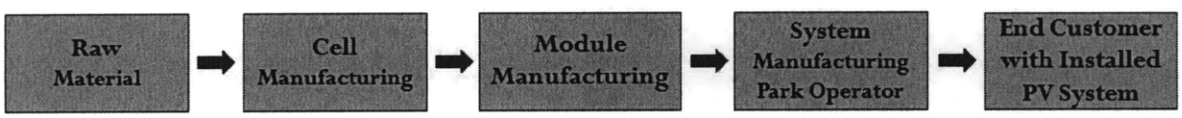


Figure 7: PV Industry Supply Chain

3.2 Solar PV System

3.2.1 Operation of Solar Cells

Solar cells are the essential parts of a PV system and the economic benefits of PV depend on the efficiency of solar cells in harvesting solar energy. There are many types of materials and technologies available to manufacture solar cells, among which three basic types of operational mechanism can be identified, namely semiconductor p-n junction solar cells, photo-electrochemical solar cells and organic polymer solar cells.

A solar cell based on semiconductor p-n junction operates by forming electron-hole pairs upon illumination, as illustrated in Figure 8. Without light illumination, a semiconductor p-n junction serves as a diode and its I-V characteristics follow the blue line on the right hand side. With light illumination, the electron-hole pairs created by photon absorption are driven by the built-in field to flow, which forms a current when the circuit is closed. When no external field is applied, the current in a circuit is called Short Circuit Current Isc, which is also the photocurrent generated. The potential under illumination when the circuit is open is called Open Circuit Voltage Voc. The Maximum Power Point depicts the I-V point where the solar cell delivers the maximum power Pmax=Im*Vm. The ratio of maximum power over the product of Isc and Voc is called Fill Factor (FF), which measures the quality of a solar cell device by the efficiency relation $\eta = \frac{I_m \cdot V_m}{Irradiance} = \frac{I_{oc} \cdot V_{oc} \cdot FF}{Irradiance}$ [20].

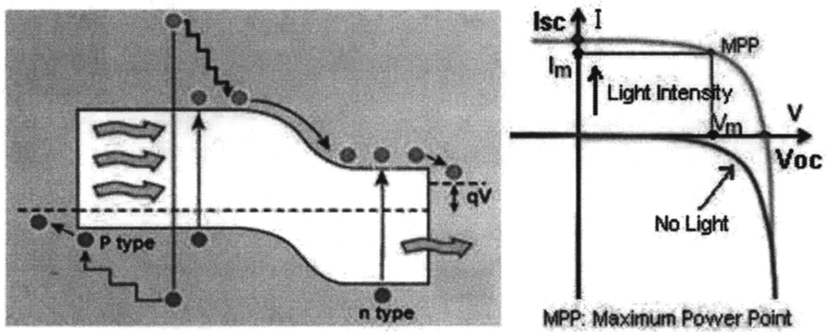


Figure 8: The Working Mechanism of a Semiconductor Solar cell

A photo-electrochemical solar cell differs from conventional semiconductor devices where the semiconductor assumes both functions of photo-carrier generation and carrier transport. For an electrochemical solar cell, instead it generates carriers with organic molecule (dye) sensitization that is similar to plant's photosynthesis with chlorophyll, and transports the generated carriers with the aid of electrochemical reactions in an electrolyte. The circuit completes with photo-generated carriers from the dye harvested by a semiconductor electrode while dye regenerated by a redox specie that will reduce at the counter-electrode where electros are supplied, as shown in Figure 9[3]. Due to the dye sensitized carrier generation mechanism,

[3] Picture Courtesy from Wikipedia: Dye Sensitized Solar Cell

electrochemical solar cell is also commonly known as Dye Sensitized Solar Cell (DSC) [21]. The IV behavior of a DSC is similar with a semiconductor solar cell explained above.

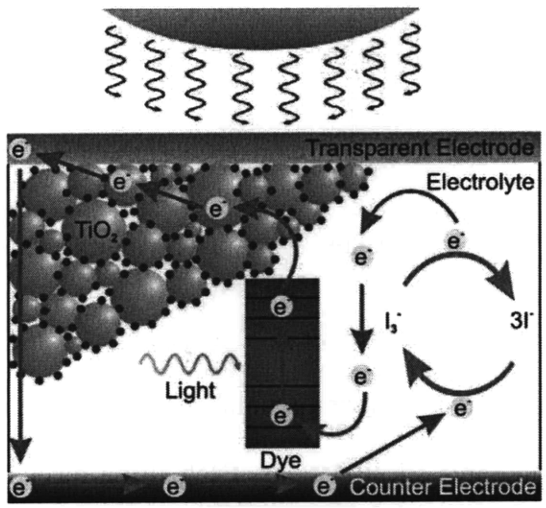


Figure 9: TiO2 Nanoparticle Based Dye-sensitized Solar Cell

A polymer based organic solar cell is a bit similar with solid-state semiconductor p-n junction solar cells in a sense that it also excites electrons from a lower band (HOMO: highest occupied molecular orbit) into an upper band (LOMO: lowest occupied molecular orbit). But the difference is that in organic semiconducting polymer based solar cells, electrons and holes are not well separated as free carriers as in solid-state semiconductor case, rather they form excitons due to localized electron and hole wave functions as well as a low dielectric constant (~3 to 4)[22]. To separate carriers, rather than a p-n junction, it utilizes a heterojunction to create the build in field. Exciton diffusion plays an important role in this process. The operation is shown below. Again the IV behavior is an organic solar cell is similar with the semiconductor solar cell explained previously.

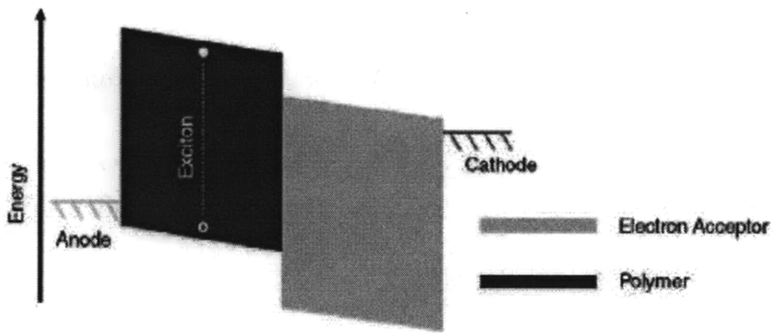


Figure 10: Working Mechanism of a Polymer Organic Solar Cell

3.2.2 PV Modules and Quality Specifications

Solar cells are connected in series/parallel to form modules that meets the required voltage, current, weight and area specifications. Each string of cells is usually protected by a bypass diode to prevent over-heating damage to the module if one cell is not functioning due to defects or shading. Since not all of the module area is covered by cells, the module's light-to-energy conversion is not rated as efficient as that rated for cells[23].

To measure a module's energy harvesting characteristics, a few parameters have to be noted. First is the **peak power** value in Wp which measures the power capacity of each module. Peak powers are always specified under standard testing conditions (1kW/m^2, AM1.5, 25℃) and sometimes under a reduced irradiance condition where Isc decreases exponentially with Voc degradation. In practical calculations, Voc can be assumed non-changing with irradiation while Isc changing with irradiance linearly[24], shown in Figure 11[4]. Next to note are those parameters that specify the efficiency of the module, as stated previously, the open circuit voltage **Voc**, short circuit current **Isc**, Maximum Power Point voltage **Vm** and Maximum Power Point current **Im**[23, 24].

---

[4] Modified graph based on one from http://www.solarpower2day.net/solar-cells/efficiency/

Another very important parameter is the **temperature coefficient** in terms of V/°C. As the temperature increases, Voc degrades rapidly while Isc increases slightly, resulting in lower peak power, shown in Figure 11. Thus the temperature coefficient of Voc is always specified for PV modules to enable practical calculations. To calculate the cell temperature, an irradiance-related equation is used where the cell temperature Tc and the ambient temperature Ta is related by Tc=Ta+(Tnoc-20)/0.8, where T_{NOC} is the standard Nominal Operating Cell Temperature characterized at 0.8kW/m^2, AM1.5 and 20°C, which is around 42°C to 46°C[24]. In a tropical climate like Singapore with an average daytime temperature above 28°C, the solar cell temperature can get as high as 60°C[25]. Therefore temperature coefficients of the installed PV modules are especially important.

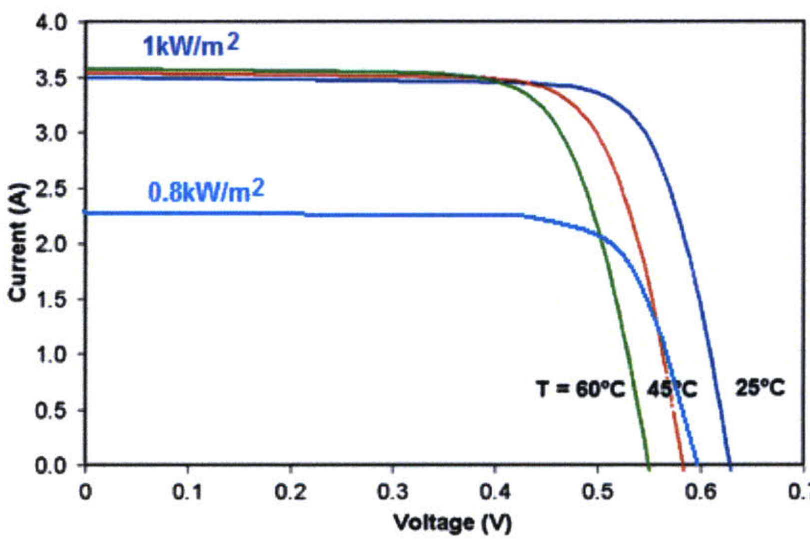


Figure 11: Temperature Effects on the IV Characteristics of a Solar Cell

Reliability of the cell shall also be taken into account. It tells how long the cell can be used while still maintain a certain efficiency. Reliability is usually indicated by module manufacturers as years of warranty. A typical warranty guarantees an 80% performance of the previous rating after 20 or 25 years of use[23].

Two practical aspects which are not directly related to energy harvesting performance is the **dimension** and **weight** of the module, which will affect how the modules can be mounted on the designated area and how strong the support has to be to bear the weight of the required modules[23].

There are several established international standards that can be followed while choosing a type of PV modules. A most complete standard is the European Standard EN50380 which requires specifications of all the above parameters[23].

3.3 Photovoltaic Systems

After PV modules are purchased, they will be installed with a set of auxiliary components to form a functioning PV system to harvest electricity. As PV systems directly produce DC electricity, a DC-to-AC inverter has to be employed before AC electric appliances can be used which includes most household and industrial appliances. Therefore, inverters are essential in both grid-tied and stand-alone PV systems. Other components in PV systems include wiring, combiner, power meters, fuse protection and in the case of standalone system, storage, which performs complementing functions like electricity guidance, stabilization and monitoring of the operation.

3.3.1 Grid-tied PV Systems

A typical residential grid-tied solar electric system is shown in Figure 12[11]. The DC electricity which comes from an array of modules is combined at an electricity combiner or junction box, before the combined DC electricity is passed to the grid tied inverter. The converted AC electricity from the inverter is distributed to the grid and/or local electricity network according to local demand under the monitoring of an import/export meter.

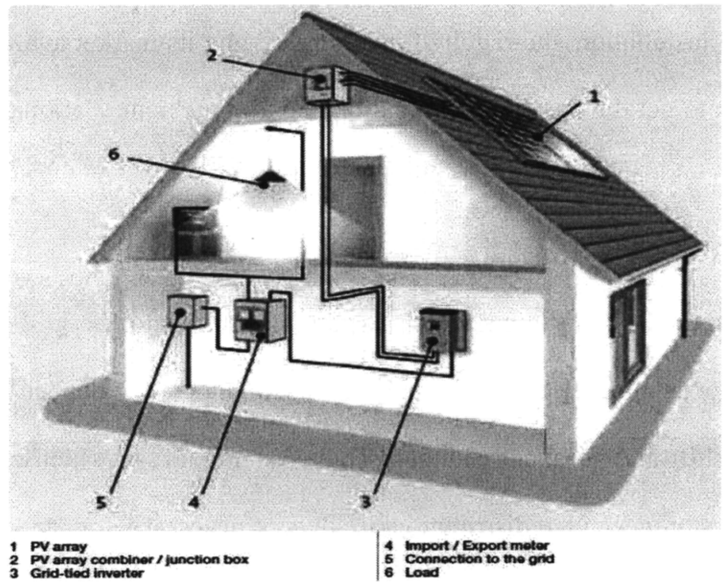


Figure 12: A Typical Grid-tied PV System

The grid-tied inverter shall be able to generate a pure electric sine wave that is synchronized to that of the grid at the specified grid voltage and frequency. Depending on the particular situation, either a Central Inverter for all the modules, several String Inverters where each string consists of a series of modules, or Module Inverters can be employed. A central inverter can be used if the output characteristics are the same in all the modules, which requires a uniform regime of solar irradiance for all modules installed. The rest types of inverters will be preferred when the solar irradiance is not uniform over all the connected panels, in cases such as partial shading and different panel inclination[11]. The grid-tied PV system in the above figure is using a central inverter.

In the situation of Singapore, Central Inverters are good candidates on the flat roofs of HDB blocks or car parks. String Inverters can be employed for BIPV systems, where panels at each façade can be connected to one separate string inverter. Module Inverters are preferable for the few houses and mansions which mostly have slanted roofs and are often located among trees and gardens. In actual installation, the required inverter size and its market availability shall also be considered in order to get the optimal combination and arrangement. National Code shall also be referred in deciding which type of inverter to use.

3.3.2 Stand-alone PV Systems

Different from Grid-tied systems which exports electricity to the grid reservoir, stand-alone systems have to balance electricity supply by itself under imbalanced solar irradiation caused by day-night shift and seasonal changes. Thus system storage which can balance solar electricity supply by storage and redistribution is always necessary for stand-alone systems. Figure 13 taken from a solar company website[26] demonstrates a typical stand-alone PV system, where the DC electricity generated by the PV array is stored in the deep cycle battery through a solar charge controller that monitors the charging voltage, charging current and battery operation conditions. AC electric appliances again can only be used after converting the DC electricity from the battery into AC electricity. A power meter is used to monitor the electricity output.

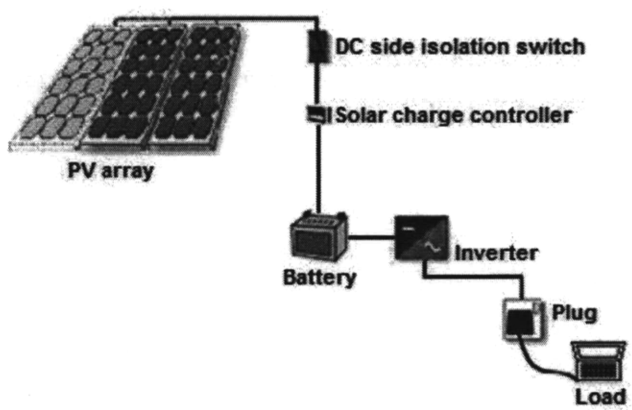


Figure 13: A Typical Stand-Alone PV System

The deep cycle-storage as illustrated is only one type of system storage. Other storage methods such as water pumping systems, spinning wheel system and flow battery systems will be elaborated in detail in Chen's thesis. The storage system voltage is usually 12VDC or 24VDC for small systems and 48VDC or higher for larger systems. In the case of a battery system, the PV module has to be able to produce a high enough voltage to charge at the specified charging voltage, which will decide how many cells are connected in series in a module. When the specific size and type of a battery is not available, serial or parallel connection is used. But as a faulty battery will form a short circuit, serial connections are always preferred to prevent energy out drain, which is also why cells in a module are mostly connected in series[11].

As batteries are very sensitive to over-charge and over-discharge, a charge controller will ensure that the battery gets disconnected with the loads when its voltage drops to a certain low level or with the PV array when its voltage researches a high enough level. These two functions are called low voltage disconnect (LVD) and high voltage disconnect (HVD) respectively. In addition, a charge controller also prevents the reverse current flow from the battery to the PV array at night[11].

The inverters in stand-alone systems are very different from grid-tied systems, as they are battery based inverters, which means their characteristics have to be matched with the changing battery voltage and the inverter has to be protected when the battery voltage gets too low. It is also required that the inverter has a range that is able to provide sufficient continuous power for all the loads as well as account for high start-up current surge[11].

4. Advancements of Solar Cell Technologies

4.1 Overview of Solar Cell Technologies

The rapid growth in world PV market has been vigorously driving and driven by PV technological developments, which has brought much advancement in PV technologies in the past half century. Based on the historic development, these technologies are widely classified into 3 generations. The first generation is crystalline Si based solar cells, including single crystalline (monocrystalline) Si based solar cell and polycrystalline (multicrystalline) Si based solar cell. The second generation is thin film based solar cells, which includes amorphous Si solar cells and II-VII elements based solar cells. Both the first and second generation solar cells are semiconductor p-n junction solar cells by operation mechanism. The third generation refers to various latest-developed new concept solar cells, which generally include high efficiency multi-spectrum III/V tandem cells, photo-electrochemical solar cells, organic solar cells and new-concept nanotechnology solar cells. The high efficiency III-V tandem solar cells and the new-concept nanotechnology solar cells generally fall into the category of semiconductor p-n junction solar cells.

Among the commercially available PV products, crystalline Si based solar cell provides the highest efficiency, but it also has the highest cost due to the large amount of high quality Si crystal used. Thin film technologies employ thin layers of semiconductor materials to produce solar cells, trading off material quality and quantity requirement for a lower cost. But due to historic reasons and the mature Si industry, Si based solar cells currently dominants the market with more than 90% market share. Table 2 illustrates the cost, efficiency and market share of various PV technologies.

Types of Solar Cells		Cell/Module Efficiency	Module Cost/Wp	Market Share
1st Generation: Crystalline Si [27]	Single Crystalline Si	24% / 15-18% [11, 28]	~US $4	89.6%
	Poly Crystalline Si	18% / 14-15% [11, 28]		
Special Applications	Crystalline GaAs	25%[27]	N.A.	N.A.
2nd Generation: Thin Film [28, 29]	Amorphous Si	12% / 10% [11, 28]	~US $1	4.2%
	CdTe and others	17%-18% / 11% [11, 28]		1%
	Cu-(In, Ga)-(S, Se)$_2$	18%-20% / 10-13% [11, 28]		0.7%
3rd Generation: In-lab Technologies	III/V Tandem Cells	Cell Efficiency 42.8% [30]	N.A.	N.A.
	Dye Sensitized Solar Cells	11.1%[31]	N.A.	N.A.
	Organic Solar Cells	1.5% -6.5%[32]	N.A.	N.A.

Table 2: Efficiency, Cost and Market Share of Various PV Technologies

4.2 Comparison of Various Types of Solar Cells

To gauge the performance of solar cells, we have to understand the factors that determine or limit their light-to-electricity conversion efficiencies. The first factor is the bandgap of the semiconductor (be it solid-state or organic) which is of critical importance in the carrier generation mechanism, as it determines the spectrum of light (photons) that can be absorbed to generate electron-hole pairs as well as how many of these carrier pairs can be collected at the contact electrodes after the photo-generation. The nonideality in the bandgap of the material is the fundamental loss mechanism which greatly limits the light conversion efficiency to below 50%[20].

The second factor lies in the recombination process where the impurities or defects in the crystal structure or at the semiconductor surface can serve as intermediate sites for the electrons promoted by photon absorption from the valence band to the conduction band to fall back to the valence band, resulting in a lower light conversion efficiency. This loss mechanism can be reduced by improving the manufacturing process[20].

The third factor is the Ohmic losses in the carrier transmission process due to series resistances. It is also highly related to the manufacturing technology and the materials involved[20].

4.2.1 First generation: Crystalline Si based Solar Cells

Due to its similarity with the well-established microelectronic industry, the silicon (Si) based first generation single crystalline and polycrystalline technology has so far been the best established and most widely employed PV technology.

With a non-direct bandgap, which limits its fundamental efficiency in light-to-electricity conversion, Si based solar cells has a theoretical light conversion efficiency of around 30% limited by the Shockley-Queisser(SQ) limit that sets a ~33% upper conversion efficiency for a homo-junction. In the ideal condition where no resistive loss is present, the lost efficiency can be broken down into 3 parts, namely heat loss due to hot carrier inelastic scattering, transmission of sub-bandgap photons, and carrier recombination. The efficiency breakdown is shown in Table 3[33]. For multicrystaline Si solar cells where there are more defect states present, the efficiency achievable is considerably lower.

Thermalization (E>Eg)	47%
Transmission (E<Eg)	18.5%
Recombination	1.5%
Remaining Efficiency	33%
Total	100%

Table 3: The Shockley Queisser Limit – Efficiency Breakdown

To date, the highest laboratory efficiency record of single crystalline silicon solar cells is 25% set last year by Professor Martin A. Green's group from University of New South Wales (UNSW) under the current international testing standards[34, 35] following a measurement of 24.7% in 1998[28, 36]. The highest laboratory efficiency record of polycrystalline silicon solar cells is 20.4%[34] set by Fraunhofer Institute for Solar Energy Systems (FhG-ISE) under the current standard following a previous record of 20.3%[37].

In terms of commercial products, the highest efficiency for single crystalline silicon PV modules is 18.4% for a commercial panel of 300W produced by SunPower[38] while the highest efficiency for polycrystalline silicon modules is 14.2% for sizes ranging from 120Wp to 200Wp from Kyocera Solar[39, 40] (by comparing products from top polycrystalline PV manufacturers). Recently, Mitsubishi Electric announced the highest efficiency commercial polycrystalline Si cells–18.9% [34, 41] while having a 13.7% module efficiency based on its 18.3 % efficient cells[42]. The new type of cells will be put into mass production in 2011[34, 41].

Table 4 summarizes the specifications of the above highest efficiency single crystalline and polycrystalline solar cells in a laboratory and a commercial setting respectively.

High Efficiency Cells & Modules	S: single P: poly	Effic.(%) Cell/Module	Wp	Area(cm^2)	Voc (V)	Jsc(mA/cm^2) or Isc (A)	FF(%)
UNSW	s-Si	25.0(da)		4.00	0.705	42.7mA/cm^2	82.8
FhG-ISE	p-Si	20.4(ap)		1.002	0.664	38.0mA/ cm^2	80.9
SunPower	s-Si	18.4(t)	300	16307.14	64.0	5.87A	79.9
KyoceraSolar	p-Si	14.2(t)	200	14107.5	32.9	8.21A	74.0

Notes: da: designed illumination area; ap: perture area; ta: total area

1. **Total area (t).** The total area of the device including the frame.
2. **Aperture area (ap).** The device is masked so that the illuminated area is smaller than the total cell or module area, but all essential components of the device such as busbars, fingers and

interconnects lie within the masked area.

3. **Designated illumination area (da).** In this case, the cell or module is masked to an area smaller than the total device area, but major cell or module components lie outside the masked area. For example, for a concentrator cell, the cell busbars would lie outside of the area designed for illumination and this area classification would be the most appropriate"[43].

Table 4: High Efficiency Laboratory and Commercial Crystalline Si PV Cells/Modules

Currently, among all types of single junction solar cells targeting at commercial and residential electricity systems, crystalline Si solar cells have the highest efficiency. But as their manufacturing requires high purity (though not as pure as those in electronics) Si for a good enough efficiency and around 50% of the module cost lies in the material (Si wafer) itself, Si solar cells also have the highest cost[44]. Also due to the additional step of single crystallization, single crystalline silicon solar cells have a higher cost than polycrystalline silicon solar cells. The present market prices for Si single crystalline solar PV modules are around $4-5/Wp and the prices for polycrystalline PV modules are slightly cheaper at $3.5-4/Wp while market average for all types of PV modules is around $4.56/Wp according to Solarbuzz™ [45].

The prices of PV modules also depend a lot on the efficiency it provides with higher prices associated with higher efficiency. For instance, price of the high efficiency solar modules from SunPower are around $7-$8/Wp and that of the modules from Kyocera is around $4-$5/Wp while the lowest retail price in market for a single crystalline silicon module is $2.80/Wp and the lowest retail price for a polycrystalline silicon module is $2.48/Wp[45].

In terms of reliability, both single crystalline and poly crystalline solar cells are sold in market with 80% efficiency warranty after 20 to 25 years (refer to appendix for product specifications).

4.2.2 Second generation: Thin Film based Solar Cells

Due to the high materials cost associated with crystalline Silicon solar cells and the Silicon shortage driven by a sustained high growth rate in the PV industry, thin-film solar cells that use only thin layers of materials deposited on substrates have been developed to reduce the cost and they begin to take up more market shares. As stated previously, thin-film solar cells are generally based on Silicon in amorphous, nanocrystalline or polycrystalline phases, and on II-VI semiconductor compounds.

For amorphous Si (a-Si) based solar cells, though with a lower manufacturing cost, they generally have less than half the efficiency of crystalline Si solar cells due to the material' disordered atomic structure. Moreover, they suffer a light-induced degradation of material quality, which reduces their efficiency further to the 4%-6% range "stabilized" after one month or two months' field exposure[46]. Multijunction hybrid cells were also developed to improve the efficiency by capturing a larger portion of the solar spectrum. These hybrid cells are either based on an a-Si top layer combined with other layers made of Germanium (Ge) alloyed a-Si or microcrystalline Si (uc-Si) alloyed a-Si. Their module efficiency was 6-7% for the Ge alloyed hybrid and 8-10% for the uc-Si hybrid[34, 46] with highest recorded cell efficiency for the former as 12.1% by United Solar System Corporation (USSC or Uni-Solar) and for the later as 11.7% by Kaneka[34]. However, they share the weaknesses associated with a-Si solar cells. Commercially, Uni-Solar and Kaneka are the best performers in the a-Si multijunction solar cell section where Uni-Solar produces Ge alloyed a-Si hybrid at a module efficiency of 6.06%[47] and Kaneka produces uc-Si hybrid at a module efficiency of 6.31%[48].

Thin film polycrystalline Si based solar cell is another type of Si based thin-film solar cells, which are produced by high temperature processing of amorphous Si layers. The resulted polycrystalline Si has a quality that is comparable with polycrystalline Si wafers that are used in polycrystalline Si PV manufacturing, thus rendering a more conductive layer that could obviate the necessity of a conducting transparent layer (CTO) that was involved in a-Si solar cell processing. The reduction of this layer reduces further the costs and at the same time eliminates a-Si's instability problem. Currently, this technology is applied into volume production by CSG Solar AG in Germany[5] with a highest recorded cell efficiency of 10.5%[34] and a commercial module efficiency of 6.51%[49].

Table 5 gives a summary of the specifications of the above stated best performance Si based thin film solar cells as well best performing modules that are available for purchase.

High Efficiency Cells & Modules	Type	Effic.(%)	Wp	Area(cm^2)	Voc (V)	Jsc(mA/cm^2) or Isc (A)	FF(%)
USSC(Uni-Solar)	a-Si(Ge)	12.1(da)		0.27	2.297	7.56mA/cm^2	69.7
Kaneka	a-Si(uc-Si)	11.7(ap)		14.23	5.462	2.99mA/cm^2	71.3
Solar AG	p-Si	10.5(ap)		94	0.492	29.7mA/cm^2	72.1
USSC(Uni-Solar)	a-Si(Ge)	6.06(t)	68	11225.06	23.1	5.1A	57.7
Kaneka	a-Si(uc-Si)	6.31(t)	60	9504	91.8	1.19A	54.9
CSG Solar AG	p-Si	6.51(t)	90	13821	82.0	1.65A	66.5
Notes: da: designed illumination area; ap: aperture area; t: total area							

Table 5 : High Efficiency Laboratory and Commercial Si Thin Film PV Cells/Modules

II-VI compounds based solar cells mainly refer to Cadmium Telluride (CdTe) solar cells and Copper Indium di-Selenide — $CuInSe_2$ (CIS) solar cells.

CdTe has been a hotly researched material for PV applications because it has the ideal bandgap to absorb the most from the solar spectrum[50]. Similarly with a-Si solar cells, CdTe solar cells are also fabricated by deposition of thin layers of materials and thus they have a lower

[5] http://www.csgsolar.com

cost as compared with crystalline Si solar cells. So far the highest record of laboratory efficiencies of a CdTe solar cell was set by National Renewable Energy Laboratory (NREL) of the United States at a value of 16.7%[34]. The highest efficiency commercial module was produced by BP Solarex at 10.9%[34]. However the element Cd is a toxic materials, which predisposes CdTe as environmentally hazardous. For this reason, previous major CdTe solar cell manufacturers including BP Solar (name changed from BP Solarex in 2001[6]) and Matsushita have abandoned the technology[46]. One of the most prosperous players in CdTe solar cell production is First Solar[7] which has been utilizing its low cost advantage resulted from the thin-film structure and high volume production. On Feb 24 2009, First Solar announced in its cooperate news that it has achieved the lowest cost of commercial modules at $0.98/Wp for the production in the 4th quarter of 2008[51] with a module conversion efficiency of 10.8%[52]. This achievement was also reflected at the year-end financial report[53].

CIS is another attractive material for solar cell applications due to its high photo-absorption coefficient and its versatility in electronic properties which can be easily manipulated by control of Copper/Indium ratios. But during its material deposition process, large stress can arise due to volume mismatches, which might delaminate the deposited film from the substrate. Thus some amount of Gallium (Ga) is added to substitute Indium (In), forming a good alloy known as CIGS, to enhance the substrate adhesion. Another advantage with CIGS solar cells is an increasing bandgap wth increasing Ga content, which can boast the open circuit voltage and reduce the number of cells interconnected in series for a module[50]. Currently, the most efficiency CIGS cell in laboratory is from NREL at 20.0% with a cell area of $0.419cm^2$ while a

[6] http://www.bp.com

[7] http://firstsolar.com

larger cell of $0.994cm^2$ has an efficiency of 19.4% [34]. The most efficiency commercial CIGS module is produced by Showa Shell Sekiyu K.K. at 80Wp with an efficiency of 9.65%[54]. Another notable manufacturer of CIGS PV modules is Nanosolar who has reported a cost of $0.99/Wp at a module efficiency of 12% made of CIGS cells that were verified to 14.6% efficient by NREL in 2006[55]. But speculations have been posed on the claimed cost and efficiency due to the company's declination in providing details due to supposed trade secret protection. So far, Nanosolar's modules are only supplied to select integrators, electric utilities and partners. Table 6 summarizes the specifications of the above stated best performance CIS thin film solar cells as well as best performing modules that are available in market for purchase.

High Efficiency Cells & Modules	Type	Effic.(%) Cell/Module	Wp	Area(cm^2)	Voc(V)	Jsc(mA/cm^2) or Isc(A)	FF(%)
NREL	CdTe	16.7(ap)		1.032	0.845	26.1mA/cm^2	75.5
NREL	CIGS	20.0(ap)		0.419	0.692	35.7mA/cm^2	81.0
First Solar	CdTe	10.8(t)	77.5	7200	90.5	1.22A	70.2
Showa Shell	CIS	10.1(t)	80	7916.35	56.5	2.26A	62.7
Nanosolar	CIGS	12.0(t)	N.A.	N.A.	N.A.	N.A.	N.A.
Notes: da: designed illumination area; ap: aperture area; t: total area							

Table 6: High Efficiency Laboratory and Commercial II-VI Thin Film PV Cells/Modules

In terms of manufacturing cost, the cost of thin film solar PVs can be up to half the cost of crystalline Si based solar cells due to the reduced material usage for thin film production and the deposition method of fabrication process. According to SolarBuzz, the lowest retail price for a thin film module is $1.76/Wp[45], which is reasonable based on the cost as low as $0.98/Wp from First Solar and $0.99/Wp from Nanosolar.

In term of reliability, the stability of all the cells tabulated in Table 6 has been verified under 800-1000 sun-hours' illumination and all the commercial products available for purchase are offered with a warranty that guarantees 90% efficiency for 10 to 12 years and 80% efficiency for 25 years (refer to product specifications in appendix).

4.2.3 Third generation: Emerging Technologies

The following categories of solar cells belong to a group of solar cells which have a high-potential in certain class of applications with their respective special features. III-V Tandem cells are especially high efficiency solar cells that involve very high cost at present due to its microchip-like fabrication and thus they are so far only used for special applications like satellites and spaceships. Electrochemical Dye Sensitized Solar Cell (DSSC) and polymer based organic solar cells are under volume production and begin to appear in the market. Polymer based organic solar cells currently still possess rather low efficiencies that cannot compete with other type of technologies. In generally, all three types of technologies are so far considered as laboratory level technologies which are not mature to compete with other technologies in the commercial utility market.

a. III-V Tandem Cells

Tandem cells or multijunction cells are solar cells that are created to capture a broader range of the solar spectrum, which can improve the efficiency of the solar cell above the SQ limit of 33% demonstrated previously in Table 3 to reach the thermal dynamic efficiency limit of 86.8%[56], as explained in Figure 14[57].

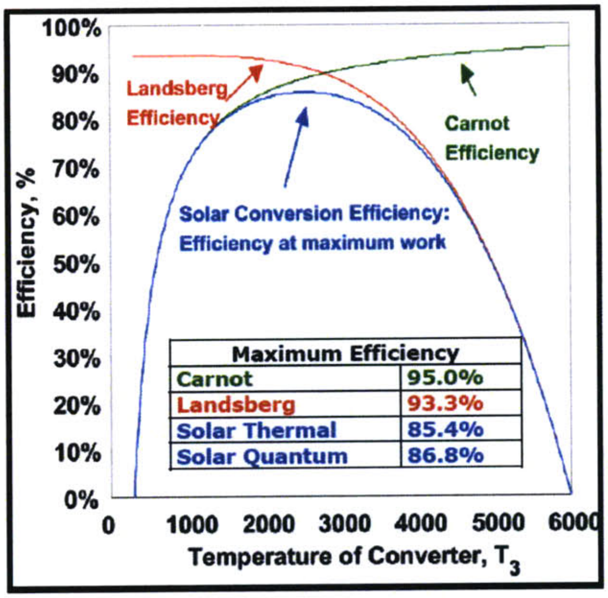


Figure 14: The Maximum Thermal Dynamic Efficiency of Solar Cells

III-V tandem cells are utilizing III-V semiconductor compounds which are direct bandgap materials to make layers of p-n junctions that capture light of different wavelengths as shown in Figure 15[57]. Upper layers are designed so as to absorb light of shorter wavelengths and be transparent to light of longer wavelengths while the lower layers are designed to absorb light of longer wavelength that passed from the previous layers.

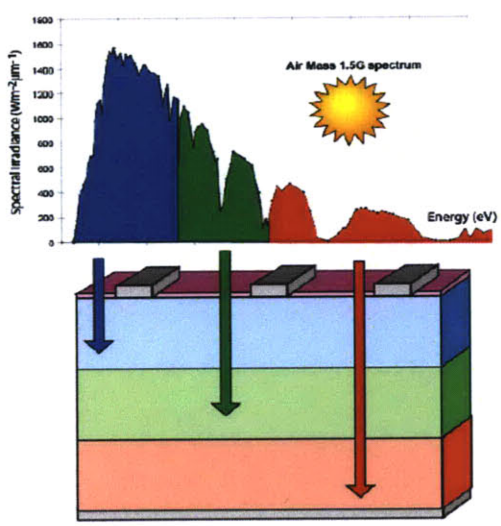


Figure 15: Operation of a Tandem Cell

Currently, due to the high cost involved in production, the one-Sun tandem cell is not able to compete with the first generation and second generation commercial solar cells with their efficiency limit as shown in Figure 16[57]. Therefore, high efficiency III-V tandem cells are mostly made in concentrator type by gathering more light into a smaller area. So far the highest efficiency of concentrator III-V tandem cell is 40.8% achieved and verified by NREL[34, 58] while the highest efficiency of a non-concentrator GaInP/GaAs/InGaAs tandem cell is 33.8%, also achieved and verified by NREL[59].

# junctions in solar cell	1 sun η	Max con. η
1 junction	30.8%	40.8%
2 junction	42.9%	55.7%
3 junction	49.3%	63.8%
∞ junction	68.2%	86.8%

Figure 16 Semiconductor Tandem Cell Efficiency Table

Commercially, there hasn't been any large tandem cell systems developed. Table 7 lists the specifications of the most efficient concentrator and non-concentrator cell.

High Efficiency Cells	Type	Effic.(%)	Wp	Area(cm^2)	Voc(V)	Jsc(mA/cm^2)	FF(%)
NREL	Conc.	40.8(ap)		N.A.	N.A.	N.A.	N.A.
NREL	Non-Conc.	33.8(ap)		0.25	2.96	13.1	86.8
Notes: da: designed illumination area; ap: aperture area; ta: total area							

Table 7: High Efficiency III-V Tandem Cells

The stability of the high efficiency III-V tandem cell is to the standard of other mature semiconductor solar cell technologies such as crystalline Si based solar cells and the high efficiency GaAs cells used in space applications. The stability of the cells in Table 7 has been verified under 800-1000 sun-hours' illumination.

b. Dye Sensitized Solar Cells

As an electrochemical cell, DSSCs have a different charge separation mechanism as explained previously. Due to this special mechanism, for a long time since 1977 when the concept of electricity generation with photo-electrochemical effect was entitled as DSC in a US patent[60], the efficiency of DSC had been too low to promise any practical applications. The present intense interest in DSC originated in an article published by Graztel's group in the Swiss Federal Institute of Technology, which reported a breakthrough efficiency of 7% with a film of TiO_2 nanoparticle sintered together as the semiconductor electrode and polypyridyl ruthenium complexes as the dye[21]. This type of solar cell is known as the "Graztel" cell, whose structure was previously shown in Figure 9.

Since 1991, there has been a growing interest in DSSC and the increasing research efforts have made various improvements to the 1991 version of Gratzel cell (shown in Figure 9). However, in terms of breakthroughs, the efficiency reached 10% in as early as 1993 as compared with the current 11.2% [61]. It took another 12 years since then to reach 11.1% efficiency for an experimental cell by Gratzel group in 2005[62] and the highest efficiency 11.1% confirmed by a public test centre is attained by Sharp in 2006 [63]. Commercially, there are a few start-up companies which have developed or out licensed the DSSC technology to produce DSC based modules or rolling sheets, such as SolarPrint[8], G24innovations(G24i)[9], DyeSol[10] and etc.

---

[8] http://www.solarprint.ie/

[9] http://www.g24i.com/

[10] http://www.dyesol.com/

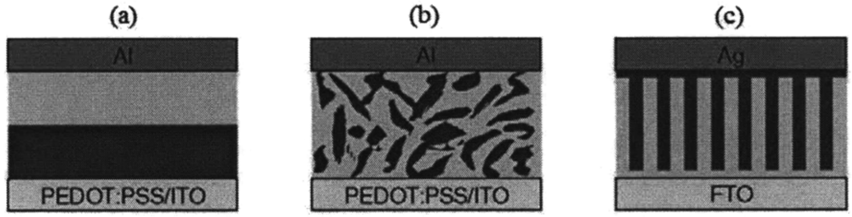
However, most of them haven't yet started volume production. Though G24i has claimed of commercial products, it has publicly displayed their products' specifications. In terms of reliability, though the DSSC from Sharp is tested for efficiency at the Japanese National Institute of Advanced Industrial Science and Technology (AIST), its stability has not been investigated. Table 8 summarizes the specifications of the DSSC from Sharp.

Manufacturer	Type	Effic.(%)	Wp	Area(cm^2)	Voc(V)	Jsc(mA/cm^2)	FF(%)
Sharp	DSSC	11.1(ap)		0.219	0.737	21.0	72.2
Notes: da: designed illumination area; ap: aperture area; ta: total area							

Table 8: High Efficiency DSSC

c. Polymer Based Organic Solar Cells

As explained in Chapter 3, polymer based organic solar cells generates excitons before the electrons and holes are separated as free carriers. The efficiency of these organic solar cells is limited by the exciton diffusion length, out of which the generated excitons have a lower probability of being harvested. Thus the active volume of the solar cells is limited to a thin layer close to the light incident interface. To overcome this limitation, a few different structures have been developed to increase the interface area and the active volume. Two most important structures are the bulk heterojunction where a heterojunction exist within an exciton length and the organic/inorganic hybrid cells where semiconductors with high electron mobility such as TiO_2 and ZnO are blended within the polymer to serve as carrier harvesting sites. Figure 17 demonstrates the two structures in comparison with the simple planar structure[22].



(a)Planar Structure (b)Bulk Heterojunction (c)Organic/Inorganic Heterojunction

Figure 17: Structures of Standard and Heterojunction Organic Solar Cells

Since the invention of the polymer based organic solar cell by Prof Alan Heeger's group from University of California at Santa Barbara (UCSB) in 1992[64], the efficiency of these organic solar cells has been under constant improvement, which is demonstrated in Figure 18[22]. So far the highest laboratory efficiency was achieved in the same group in UCSB at 5.5% for a bulk heterojunction cell[65]. Tandem cells based on organic polymers have also been investigated to boast the efficiency. The highest efficiency for a polymer based tandem organic solar cell is also attained in Prof Heeger's group with a value of 6.5% and more notably with a all-solution based fabrication process[66].

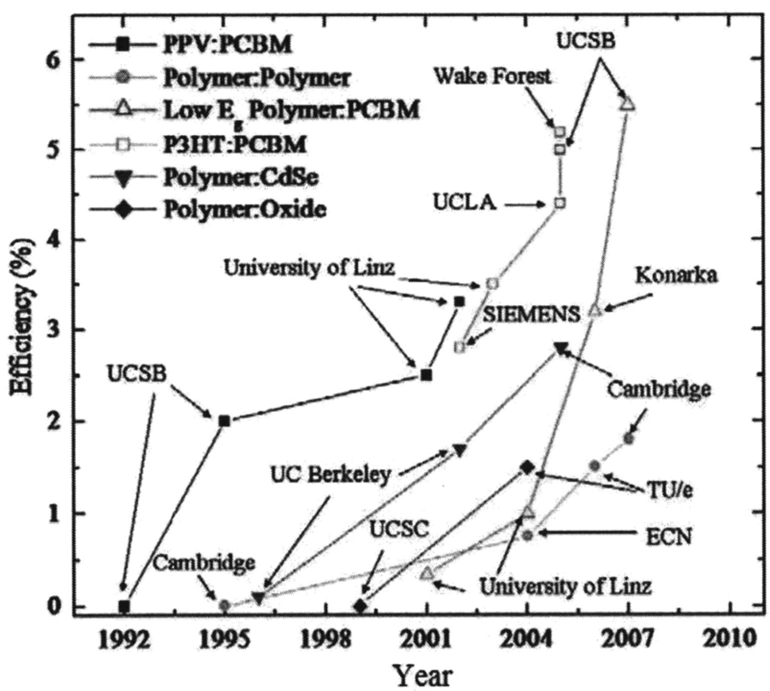


Figure 18: Development of Polymer-based Solar Cells

Commercially, due to the low efficiency and untested reliability issue, organic solar cells are not yet able to compete with other type of solar cells in commercial large scale electricity generation. Startup companies using this technology such as Konarka[11] are only targeting small and portable devices with emphasis on its advantage of flexibility. Table 9 lists the specifications of the two solar cells with the highest efficiency record.

Manufacturer	Type	Effic.(%)	Wp	Area(cm^2)	Voc(V)	Jsc(mA/cm^2)	FF(%)
UCSD	Heterojunction	5.5		0.17	0.62	16.2	55.0
UCSD	Tandem	6.5		N.A.	1.24	7.8	67.0
Notes: area specifications were not fully provided.							

Table 9: High Efficiency Polymer Solar Cells

4.2.4 Future Aspects of Efficiency Improvement and Cost Reduction

To predict how each technology will perform in future, the historic developments of each technology shall be discussed and compared. Figure 19[56] demonstrates the historical developments of the various type of solar cell technologies discussed previously from 1976 to 2004. It is obvious that these various types of technologies have been evolving at a similar rate except organic solar cells at their first 15 to 18 years. Also, multijunction concentrator solar cells have been improving at a constant rate while the rest begin to slow down to a stable value. This trend could be attributed to the average learning curve of worldwide research activities. The relatively higher rate of development for multijunction concentrator shall be attributed to a better understanding of the fundamental semiconductor science and engineering that was gained through the development of the microelectronics industry. The relatively slow development of

[11] http://www.konarka.com/

organic solar cell is in the same principle due to the lack of fundamental understanding in molecular electronics.

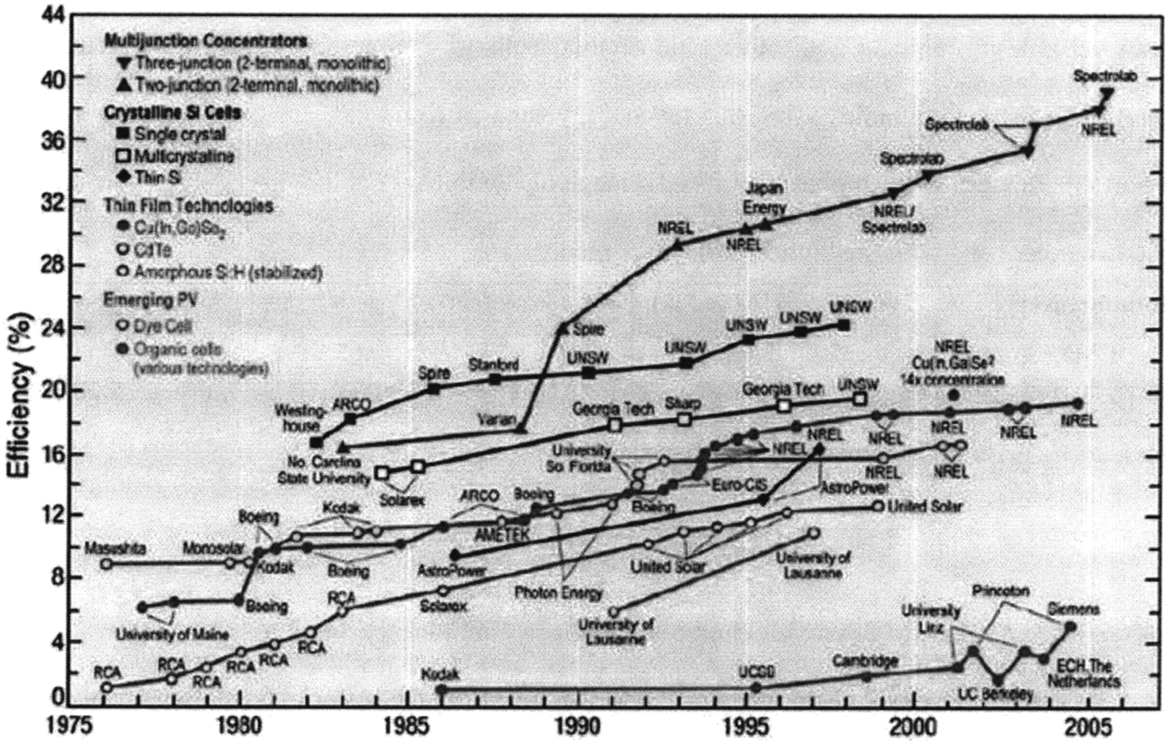


Figure 19: Improvements in Solar Cell Efficiency by System, from 1976 to 2004

In terms of manufacturing cost of PV modules, there has shown a 20% cost reduction trend for every doubling of production volume from the historic cost tracking of PV modules since 1976 as shown in Figure 20[56]. As the global cumulative installation volume at the end of 2008 has reached 14.7GWp[67], by extrapolating the 80% cost learning curve, the cost shall get below \$1/Wp for thin film modules and around \$1.5/Wp for crystalline Si based modules. Currently, the lowest cost for thin film module is around \$1/Wp by First Solar[51] and costs for crystalline Si based modules are still at the \$1.7 – \$2.5/Wp range[68]. Thus the current status reflects a slower learning progress. Based on the current growth rate of 40% in production, it takes every 2 (1.4x1.4) years for each doubling of production volume, thus an 80% to 90% cost reduction. It will then take another 8 to 17 years(4 to 8.7 times doubling) to bring down the \$1/Wp cost to the targeted \$0.40/Wp for competitive large scale applications[56].

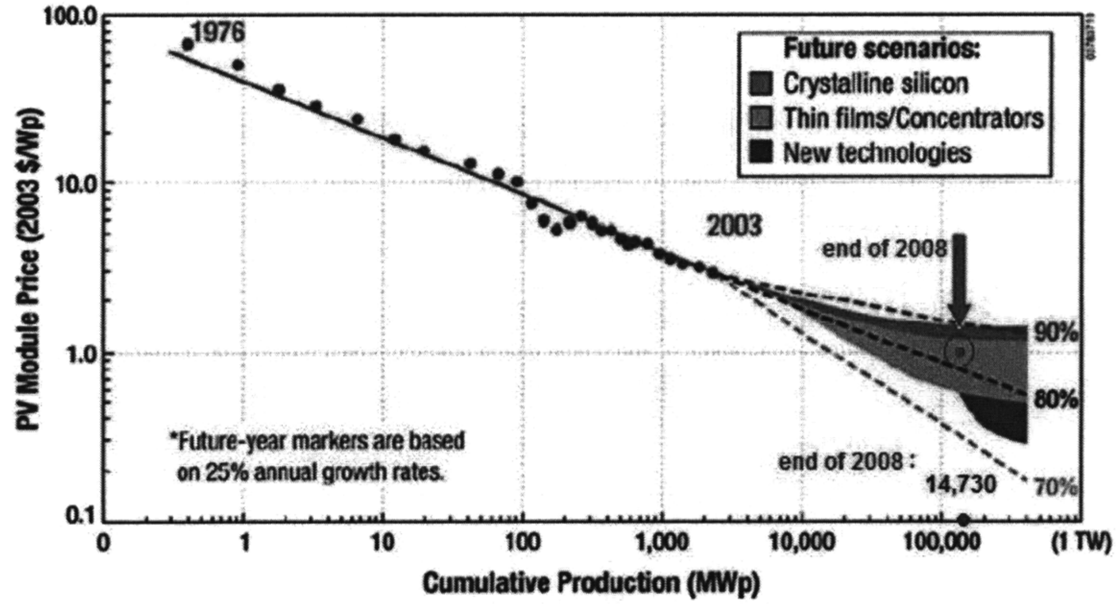


Figure 20: PV Module Cost Reduction Trend with Time and Production Volume

However, the above postulations are based on the case that the raw materials production volume can expand without causing materials supply shortage which would bring deviations to the raw materials price prediction. In fact, in the past several year, global PV market expansion and the high market share of Si based solar module production have already created a Si supply shortage which have prevented significant cost reduction for crystalline Si module since 2005[56]. This was also one of the reasons that thin-film products which only require thin layers of materials that are of several microns thick successfully entered the PV market. And many thin-film solar cell manufacturing lines, either Si-based or II-VII semiconductor based, has proliferated[46].

However due to the low abundance of the related semiconductor II-VII elements on earth as shown in Figure 21[69], the prices of some scarce materials such as Se, might eventually rise up when the production capacity cannot meet the future demands of the industry, thus depriving II-VII elements based solar technologies of the current relative advantage of cheaper materials. Therefore in order to achieve a long term market advantage in PV module production, new technological breakthroughs towards lower cost and higher efficiency are to be developed.

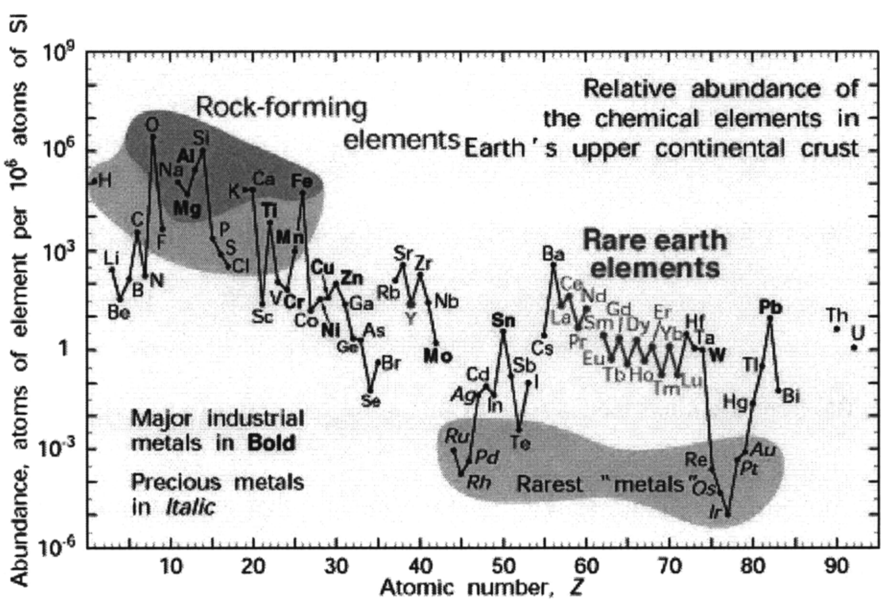


Figure 21: Relative Abundance of Elements in the Earth Crust

4.3 Best Performance Modules under Singapore Climate

4.3.1 Summary of the Characteristics of Solar Irradiation in Singapore

From Chapter 2 and Chapter 3, the average daily solar irradiation in Singapore is $4.0kWh/m^2$[19] which determines how much energy available for solar panels to harvest as electricity. Also, a daily irradiance following the track shown in Figure 6 and a panel temperature at 60°C[25] on a sunny day will help us to estimate the peak electricity supply from a solar PV system.

4.3.2 Best Performance Commercial PV Modules under SG Climate Condition

Table 10 summarizes the best-performance laboratory solar cells and best-performance commercial modules for each solar cell technology based on their efficiency comparison. The type of technology serves as a bench mark to compare the cost, where crystalline Si based solar cells have the highest cost and thin film solar cell technologies have relative lower cost.

Manufacturer of Cells/Modules	Type	Effic.(%) Cell/Module	Wp	Area(cm^2)	Voc (V)	Jsc(mA/cm^2) or Isc (A)	FF(%)
Best-Performance Cells							
UNSW	s-Si	25.0		4.00(da)	0.705	42.7mA/cm^2	82.8
FhG-ISE	p-Si	20.4		1.002(ap)	0.664	38.0mA/cm^2	80.9
Uni-Solar	a-Si(Ge)	12.1		0.27(da)	2.297	7.56mA/cm^2	69.7
Kaneka	a-Si(uc-Si)	11.7		14.23(ap)	5.462	2.99mA/cm^2	71.3
Solar AG	p-Si	10.5		94(ap)	0.492	29.7mA/cm^2	72.1
NREL	CdTe	16.7		1.032(ap)	0.845	26.1mA/cm^2	75.5
NREL	CIGS	20.0		0.419(ap)	0.692	35.7mA/cm^2	81.0
Sharp	DSSC	11.1		0.219(ap)	0.737	21.0mA/cm^2	72.2
UCSD	Hetero-Organic	5.5		0.17	0.62	16.2mA/cm^2	55.0
UCSD	Tandem	6.5		N.A.	1.24	7.8mA/cm^2	67.0
Best-Performance Modules							
SunPower	s-Si	18.4	300	16307.14(t)	64.0	5.87A	79.9
Kyocera	p-Si	14.2	200	14107.5(t)	32.9	8.21A	74.0
Uni-Solar	a-Si(Ge)	6.06	68	11225.06(t)	23.1	5.1A	57.8
Kaneka	a-Si(uc-Si)	6.31	60	9504.0(t)	91.8	1.19A	54.9
CSG Solar AG	p-Si	6.50	90	13820.6(t)	82	1.65A	66.5
First Solar	CdTe	10.8	77.5	7200(t)	90.5	1.22A	70.2
Showa Shell	CIS	10.1	80	7916.35(t)	56.5	2.26A	62.7
Nanosolar	CIGS	12.0	N.A.	N.A.	N.A.	N.A.	N.A.
Notes: da: designed illumination area; ap: perture area; t: total area							

Table 10: Summary of Best Performance Laboratory Cells and Commercial Modules

Comparing the best-performance modules, crystalline Si (either single crystalline or polycrystalline) based solar cells processes the best efficiency performance but they also have the highest cost. Among thin-film based technologies, CdTe based and CIGS based solar cells are able to have better performance than Si based thin film technologies while having a similar cost with its thin film process. As DSSC and polymer based organic solar cells are not yet mature and reliable, they will not be considered in our following analysis for PV system integrated EV charging stations.

In terms of the relative position of cost and efficiency, we can see from Figure 22 that second generation thin-film solar cell technologies have a higher efficiency/cost ratio as compared to first generation crystalline Si based technologies. Especially, from the previous efficiency comparisons, thin film solar cell technologies such as CIGS and CdTe at their highest laboratory efficiencies are already comparable with commercial crystalline Si products while requiring lower cost and sold at lower prices. Thus the second generation CdTe and CIGS based thin film solar cells technologies seem to be the most promising technologies to compete in the Si dominated market for electricity generation applications. Among the listed module suppliers, First Solar and Showa Shell provide the overall good quality modules available for sale.

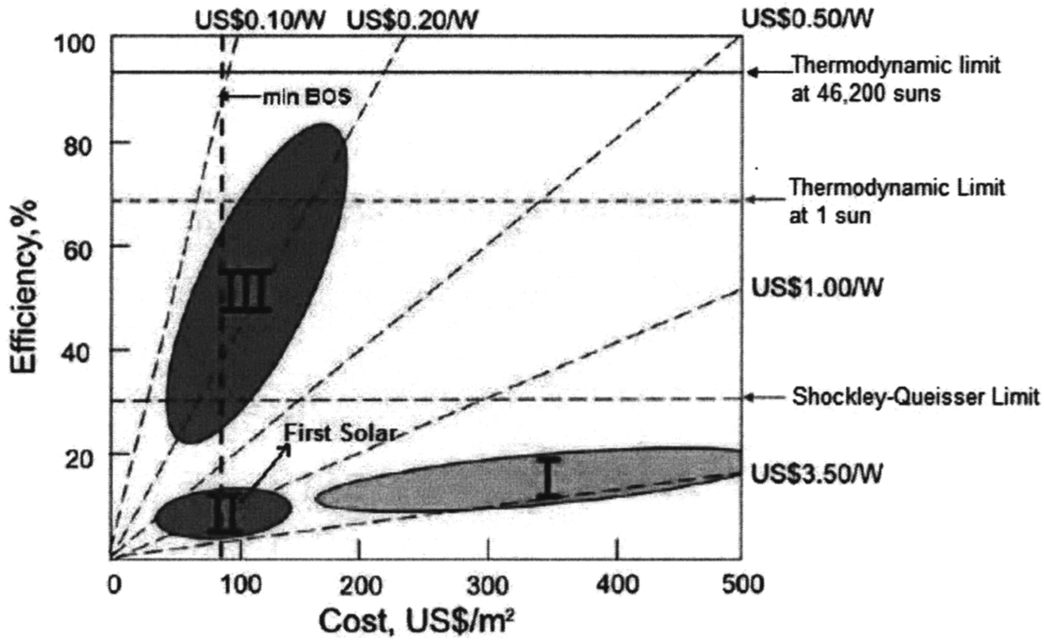


Figure 22: Solar Cell Efficiency vs. Cost

For PV systems installed in Singapore, the performance specifications of the above stated modules will deviate from the standard rated values. By applying the standard temperature coefficients and assuming a fixed Fill Factor[24], we can calculate the operating efficiencies of the above available best-performance modules from various suppliers under the Singapore climate condition (60 °C and high humidity) with the formula Efficiency= Output Power at 60 °C/Solar Irradiance on the module. Table 11 summarizes the calculated results.

Performance of Modules under Singapore Climate Condition								
Module Manufacturer	Cell Type	Effic.(%)	Wp	Voc Co. (mV/°C)	Isc Co. (mA/°C)	Pm Co.(/°C)	Pm at 60 °C	Effic.(%) at 60 °C
SunPower	s-Si	18.4	300	–176.6	3.50	-0.38%	276.52	17.0
Kyocera	p-Si	14.2	200	-123.0	3.18	-0.34%	176.19	12.5
Uni-Solar	a-Si(Ge)	6.1	68	-87.8	5.10	-0.21%	61.02	5.4
Kaneka	a-Si(uc-Si)	6.3	60	-280	0.89	-0.23%	55.00	5.8
CSG Solar AG	p-Si	6.5	90	-390.0	1.5	-0.39%	77.41	5.6
First Solar	CdTe	10.8	77.5	-226.3	0.49	-0.25%	71.71	10.0
Showa Shell	CIS	10.1	80	N.A.	N.A.	t.t.: 20%	64.00	8.1

Table 11: Performance of PV Modules under Singapore Climate Condition

From Table 11, we can see that in terms of efficiency, First Solar is able to deliver a module efficiency of 10.0% at a high cell temperature of 60 °C, which is more than 4% higher than Si-based thin film modules and only 2.5% lowered than the 12.5% efficiency polycrystalline Si module from Kyocera. But it is able to deliver the lowest cost at $0.99/Wp as compared to around $2.00/Wp[56] for crystalline Si based PV modules. Thus in terms of efficiency and cost ratio, which serves as a figure of merit in land-scarce and tropical Singapore, First Solar offers the best solar modules overall.

In Section 5, First Solar's module efficiency and cost will serve as an indicator for state of the art PV electricity generation system analysis.

5. PV Electricity Cost in Singapore

5.1 Business Model

As mentioned in Part 1, with a population of 4,839.4 thousand [70] at a limited land area of 707.1 km^2 [71], Singapore is the second most densely populated country in the world with 6489 (in 2008) people/km^2. Due to this high population concentration in Singapore, more than 85%[72] of the people in Singapore live in multi-storey apartments developed by Housing Development Board called HDB blocks that have at least 12 and up to 40 storeys where each floor has around 4 to 6 flats[12]. A small percentage of people live in houses that are similar to those common in North America.

For an HDB block developed by the government, the operating of the PV system can be leased by the government to outside vendors who can profit from selling electricity. For an independent private house, the PV system will be owned by the house owner who can use the electricity generated to offset his/her electricity bills and sell the excess to the grid. Based on the two cases, the PV system pay back will be modeled under the Singapore climate condition and the economic feasibility of installing PV systems in Singapore will be evaluated. The details are summarized in Table 12.

Models of PV System	Usable Area for PV Panels
HDB Block Model	Flat HDB Block Roof and/or Flat Multi-storey Carpark Roof
Private House Model	Flat/Slanted Roof of the House

Table 12: Models of PV System in Singapore

[12] http://www.hdb.gov.sg/

5.2 Regulations on PV Electricity Generation and Wholesale

In Singapore, electricity licensing is governed by Energy Market Authority (EMA) which has published a PV handbook on the issues related to PV system installation and operation in Singapore.

To build a PV system, a Generation License from EMA is required for a PV system if the system has no less than 1MW generation capacity. The application details are documented at the EMA website[73]. If electricity generated from the PV system is only for residential consumption, no registration of the system with the National Electricity Market of Singapore (NEMS) is required. However, if the operator of the PV system wishes to sell and get paid for the electricity sold to the grid, a Wholesaler (Generation) License has to be obtained from EMA and Registration to NEMS for the wholesale of electricity shall also be made, of which the procedure is detailed out in the "Market Administration Market Manual" published by the Energy Market Company (EMC)[74]. Therefore, for a grid tied system that could sell the excess electricity to the grid, it is required for the operator to obtain an installation license and register the PV system with NEMS for sales of electricity. But for standalone systems that generates electricity for self consumption, only a generation license might be required and it is so only if the system has a generation capacity that exceeds 1MW which is not common in Singapore[75].

After the mechanical installation of the panels, the electrical installation shall be carried out or supervised by a Licensed Electrical Worker who can be an electrician, an electrical technician or an electrical engineer depending on the voltage and load of the installation. For loads that are no more than 45kW with a voltage that does not exceed 1000V, an electrician is qualified enough for the work. For loads that are above 45kW but do not exceed 150kW in the designed load and 500kW in actual operational load, with a voltage not exceeding 1000V, an electrical technician shall be engaged. For any load or voltage above the stipulated values, an licensed electrical engineer is required[75].

An electrical installation license from EMA might be needed to install the PV electrical system if the owner/operator hasn't obtained an electrical installation from previous installation of electrical applications. A new license is not required if the operator already has an electrical installation license. Generally, the LEW will be able to advise the operator on whether an installation license is required[75].

To connect to the grid for a grid-connected system, the appointed LEW has to consult Singapore Power PowerGrid (SPPG) on the connection scheme and the technical requirements which are governed by the Transmission Code and the Metering Code published by EMA[75]. The details on application of electrical connection to the power grid (owned by Singapore Power Ltd) is documented in SPPG's handbook[76].

To sell electricity from the PV system to the market, the price paid to operator of the PV system will be the prevailing spot electricity price which is updated every half an hour depends on the demand[75]. The operator will also be subjected to charges such as EMC fee, PSO fee, and regulation reserve ("AFP") price in respect of the gross generation output from the PV system for the service and resource provided by the market[75, 77]. Electricity sales activities shall also comply with the market rules[78].

5.3 Cost of a PV System

5.3.1 Overview

a. Direct Cost of a PV System

The direct cost of a PV system consists of hardware cost, installation cost and maintenance cost. Hardware in a grid-connected system whose operation is shown in Figure 23 includes PV modules, inverter, power conditioning regulators and power controlling meters (load centre). In the case of a stand-alone system whose operation is shown in Figure 24, it also includes an energy storage system and a charge regulator that provides protection to the battery by preventing over-charge and over-discharge.

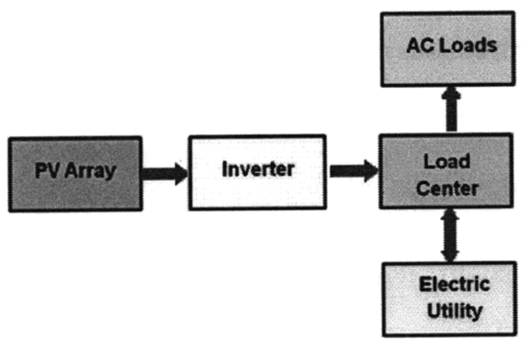


Figure 23: Functioning Diagram of a Grid-Connected System

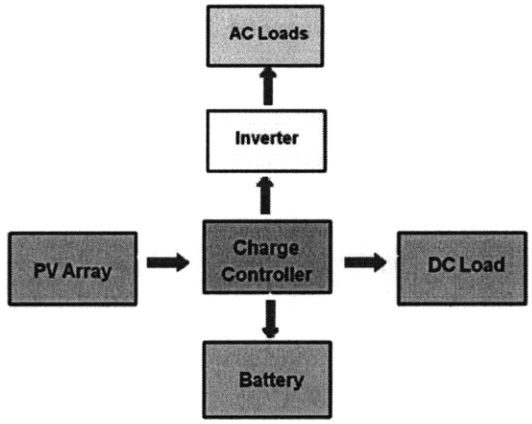


Figure 24: Functioning Diagram of a Stand-alone System

In terms of installed cost breakdown, it can be quite different for grid-tied systems and stand-alone systems due to the generally high cost storage system. For grid-connected systems which account for around 90% of total installed systems worldwide at the end of 2007[79], module cost is the highest portion of cost that generally accounts for an average of 50% of the total installed cost from 1998 to 2007 and around 65% at the end of 2007[80]. Figure 25 shows the cost breakdown over 10 years from 1998 to 2007 for the grid-tied systems installed in the United States[80]. From this figure, we can see that over the years, both module cost and non-module cost have dropped. But from 2002 to 2007, cost reduction has mainly been attributed to non-module cost which has also stagnated since 2005. It again proves the necessity of new technological breakthroughs in solar cell technology in order to bring down the cost of grid-connected systems in the near future.

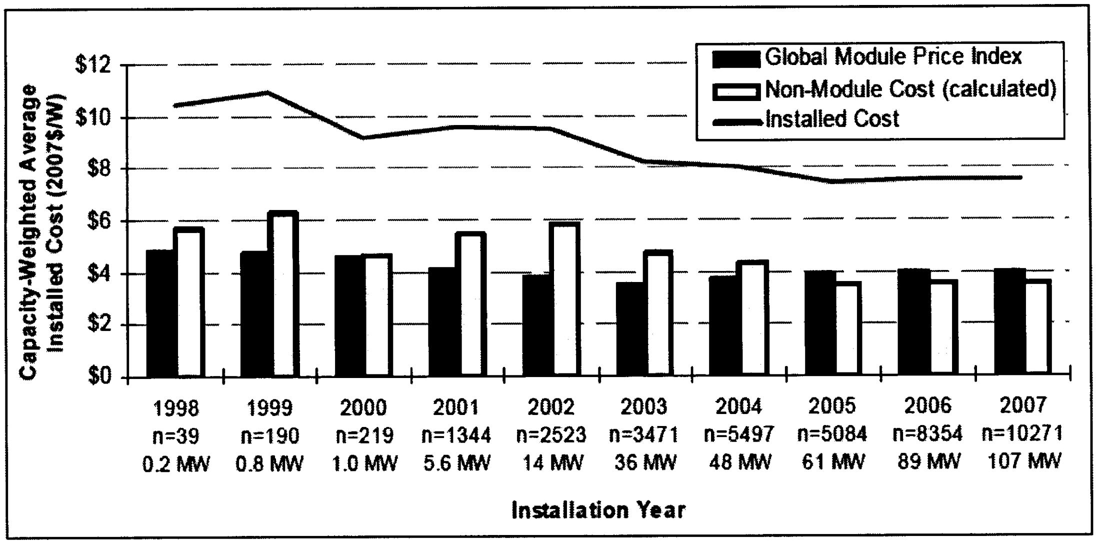


Figure 25: Cost Breakdown for Grid-Tied Systems in the United States

For stand-alone systems, the cost is highly dependent on the system storage (e.g. batteries) cost. Figure 26[81] demonstrates the cost breakdown for a stand-alone system with system storage at the time of initial investment and over a PV system life time of 20 years. We can see that in this case the PV module only represents around 1/3 of the total initial investment cost, while system storage (batteries) almost cost as much as the PV modules. Especially when PV module's lifetime is taken into consideration, the storage becomes the most significant part of cost, which is more than twice the module cost due to battery replacements during the PV's life time. In such cases, even when the module cost drops to zero, the system cost will only be reduced by around 20%.

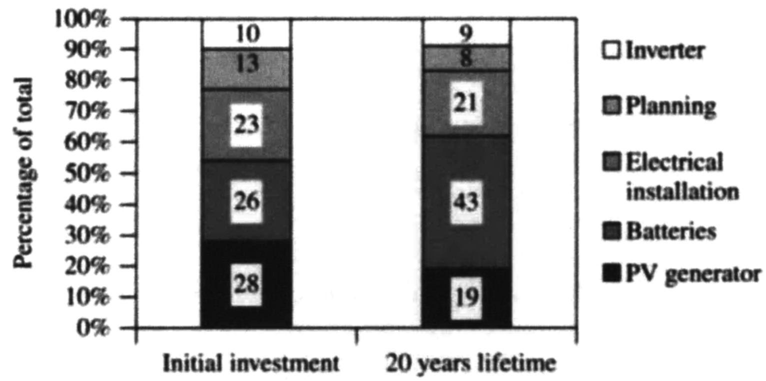


Figure 26: Cost Breakdown for a Stand-alone System in the United States

Thus from such a comparison, we can see that when designing a PV system, especially when the size of the system is substantial, grid-tied systems shall be considered first. Even in the case that the PV system is located in a remote area where grid is not available thus stand-alone must be used, sizing of the battery shall be carefully examined in order to reduce the cost of the system storage.

b. Indirect Cost of a PV System

The indirect cost of installing a PV system includes related licensing fees and taxation. The licensing fees in Singapore might include electricity generation license fee to EMA, market participation registration fees to NEMS and electrical installation license fee to EMA. For a grid-tied system, taxation applies to the income gained from selling electricity to the grid.

5.3.2 Cost and Price of Each Component

a. Modules

Figure 27[82] demonstrates the average module cost and price for crystalline Si based technology and various thin film based technologies in the industry. We can see that currently among the three most representative thin film based solar cell technologies, namely amorphous

Si (a-Si), CdTe and CIGS, CdTe has the lowest cost at around \$1.1/Wp while that of a-Si is slightly higher at \$1.4/Wp and that of CIGS is the highest at \$1.7/Wp. The cost of crystalline Si based solar PV modules is approximately twice that of CdTe thin film based solar PV modules at more than \$2/Wp.

As the analysis will be based on CdTe modules from First Solar, who has announced a production cost of \$0.98/Wp[51], the module price of \$2.0/Wp will be used as the current standard in subsequent analysis. An average PV efficiency of 95% will be used to account for the loss in module wiring and rating deviations based on a similar model done in Malaysia recently[83].

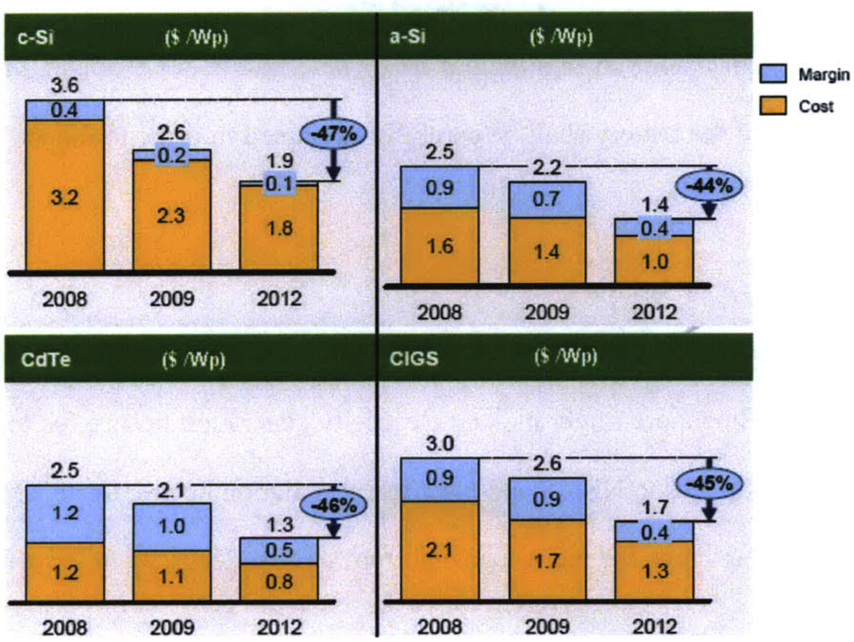


Figure 27: Average Module Price and Cost by Technology

b. Inverter

Inverter is another important component in the PV system which accounts for around 10-20% of the initial system cost and even higher percentages during the lifetime of the PV system due to their limited lifetime of around 5-10 years[84]. Therefore it is usually known in the PV industry as the weakest part of the system besides batteries due to the reliability issues. Currently, commercial inverters are generally offered with a warranty of 5-10 years[85].

In terms of prices, there has shown a 10% learning rate in inverter cost reduction as compared to the 20% learning rate in PV module cost reduction mentioned previously in Section 4.2.4, meaning that the inverter prices drop by 10% with every doubling of cumulative production[84]. With a forecast growth rate of 30% in the next 4 years[86], the price reduction trend can be predicted with the plot shown in Figure 28. It would take around 8 years for the cumulative production to double 3 times (1.3^8= 8.15), thus 73% price reduction with 90% learning rate (90%^3= 72.9%). Currently, the reported average single inverter price from SolarBuzz[13] is around $0.72/Wp. As prices of inverters for large systems (>70kW) is less than half the price of those for small systems, the current price of a large system is around $0.35/Wp[84].

As in our subsequent analysis for PV systems in Singapore, a single central inverter of the correct size will be used, we are going to take a price of $0.72/Wp for small systems while a price of $0.35/Wp for large systems (>70kW). Again based on the real model done in Malaysia, an inverter efficiency of 95% will be assumed[83].

[13] http://www.solarbuzz.com

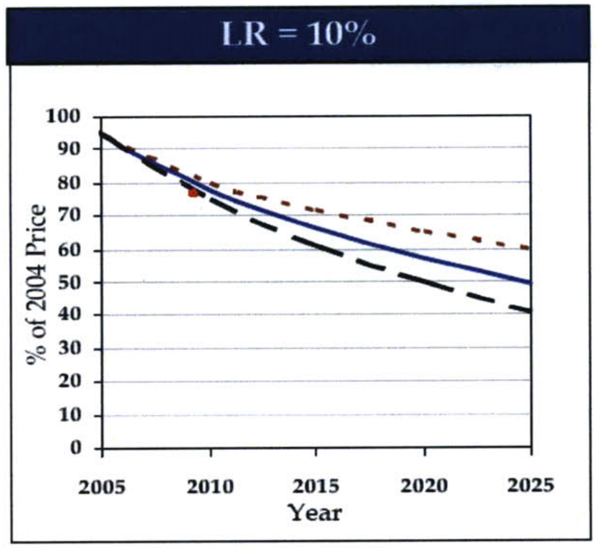


Figure 28: Average Inverter Price as a Percentage of 2004 Price

c. Installation Cost (Wiring, fuses, switches, meters, etc)

Installation cost of the system also depends on the size of the system. The installation rate in Singapore is estimated based on the rate in the United States discounted by the electrical engineer wage ratio, as PV system installation is not yet a well established industry in Singapore. The US rate given by National Renewable Energy Laboratory is around $745 per kW installation[87], with a wage ratio of 1.47 estimated from the average electrical engineer wage data provided by United States Bureau of Labor Statistics and Singapore Ministry of Manpower. Thus with an exchange rate from USD to SGD of 1.44, the installation cost in Singapore is $509/kW ($745/1.47). An efficiency of 98% will be used to account for wiring, fuses, switches and meters [83].

d. Other Hardware (Charge Regulator and System Storage)

In stand-alone systems where storage is required, a charge regulator is employed. As the cost of charge regulator is small as compared with the cost of system storage, the market average price is $5.8/Amp according to SolarBuzz[88]. The average price of the system battery storage is

$2.05/Wh, resulting in a storage cost higher than the modules cost[88]. The energy efficiency is around 80-90% for the charge controller and battery storage components[83]. Here an efficiency of 90% will be assumed.

e. Maintenance

The maintenance cost is estimated in the same way as the installation cost. With a rate of $74/kW-yr, the installation cost in Singapore is estimated at $50.5/kW-yr ($74/1.47).

f. Licensing

For PV system installation in Singapore, the wholesaler licensing fee payable to EMA is SGD $100 per annum and electrical installation license fee to EMA is SGD $100 per annum[75]. The Market Registration Fee to the NEMS has been removed since June 2007 to promote energy generation with renewable such as solar, wind and etc.[89].

5.4 Sizing of HDB PV System and Private House PV System

5.4.1 HDB System

In Singapore, for an HDB block with an average of 6 flats on one floor, it generally has 72 (12 floors x6 flats) to 195 (39 floors x 5 flats) flats/families that share the common roof area where a PV system can be deployed at the roof top. Including its auxiliary areas like multi-storey car parks which usually has 4 to 7 storeys and is shared by 4 blocks, the total available roof area for people of 4 blocks will be the roof area of these 4 blocks plus the roof area of the multi-storey park which typically has a roof area of half the total block area[90].

As an HDB block with 6 flats per floor typical has 4 flats of 4-room type and the other 2 of 5-room type, we can estimate its total floor area by adding up the following components:

1. No. of 4-room flat*standard 4 room floor area

2. No. of 5-room flat*standard 5-room floor area
3. Excess area (corridor, lifts and etc.)n

As a standard 4-room flat has an area of 85m^2 and a standard 5-room flat has an area of 110m^2 [91], by taking an excess area which is approximately equal to a 4-room flat, the total floor area of 4 blocks can be estimated. Including the area of the auxiliary 4-storey car park, which has a roof area that is about the roof area of two such blocks, the total available roof area can be calculated in the following table.

A standard HDB block	No. of 4-room flat	No. of 5-room flat
	4	2
Standard Area(m2)	85	110
Floor Area(m2)	340	220
Flat Floor Area(m2)	560	
Excess Area(m2)	85	
1 HDB Roof Area(m2)	645	
Total HDB Roof Area(m2)	2580	
Car Park Roof Area (m2)	1290	
Total Roof Area(m2)	3870	

Table 13: HDB-Carpark Model Available Roof Area Estimation

5.4.2 Private House System

For a private house model, as we assume the owner of the house is to offset the electrical bills, thus the total electricity consumption of all electrical appliances shall be estimated. As the load demand in a typical private house in Singapore is around the same with that in its neighbor Malaysia, the recently reported Malaysian private house loading estimate will be used, which is shown in the following Table 14[83]. The total household electricity consumption per day is 3.56kWh.

Appliance	Quantity	Nominal power (W)	Working hours (h)	Watt-hours (Wh)
Fan	2	25	6	300
Radio	1	25	2	50
Washing Machine	1	100	1	100
Kitchen Appliances	2	50	4	400
Refrigerator	1	50	24	1200
Computer	1	100	2	200
Air-conditioner	1	100	6	600
Video player	1	30	2	60
Television	1	50	4	200
Lights	5	15	6	450
Total				3560

Table 14: Load Demand of Typical Houses in Tropical Southeast Asia

As the floor area of a typical house with 4 rooms on the ground floor is around the same with that of an HDB 4-room flat, a floor area of $340m^2$ shall be used. With a 30% percent tilt angle which is typical for standard private houses, then the roof area is calculated as follows:

$$\text{Roof Area} = 340m^2/\cos(30^{\circ}) = 392.6\ m^2$$

Therefore, the total available horizontal roof area is 340 m^2 and tilted area for installation of panels is 392.6 m^2.

5.5 Electricity Cost of Grid-tied System

For grid-tied systems, the system storage and storage charge regulators are not necessary, thus they will not be considered in the cost modeling of grid-tied systems in this section.

5.5.1 HDB-Carpark Model

5.5.1.1 Evaluation without Loan Financing

As the loan interest rate is generally high when large amount of capital cost is financed, the Levelized Cost of Energy (LCOE= electricity cost based on net present capital cost) can be very different between the case without loan financing and with loan financing. Thus these two cases will be separately discussed. The loan interest rate is assumed to be 10% while the discount rate is at 1%.

a. Cost Estimation

As estimated in section 5.4.1, the total available area of an HDB-Carpark unit which consists of 4-HDB blocks and one multi-storey car park is $3870m^2$. We assume 90% of the area is for modules while the rest is for installation overhead, as shown in Table 15. Thus based on the radiation data of Singapore as shown in Table 16, with the 77.5Wp module FS-277 from First Solar, whose specifications and operational peak power of 72Wp at 60°C are listed in Table 17, we can estimate the number of modules required to cover such an area and the total peak power and the total energy generation per day, as shown in Table 18. The operation specifications are shown in Table 19. The estimated time of operation is 20 years, which is a conservative lifetime specification for solar modules with 25 years of warranty. An interest rate of 1% is used to discount future cost that incurred during the 20-year operational period of the system. The specification of inverter is shown in Table 20, an inverter price of $0.35/Wp is used as total peak power is large than 70kW. The efficiency derating due to system loss is shown in Table 21, with an aggregate efficiency of 80%. The cost of installation is calculated as $509 times the system capacity in Wp. The next part of cost to be specified is the maintenance and licensing cost, which are variables costs that incur annually for the whole 20 operation years. The variable costs are discounted to Net Present Values (NPV) based on the 1% interest rate as shown in Table 22.

One thing to note is that the lifetime of the inverter is around 10 years, which is half of the system operational life time. Thus a new inverter is assumed to be bought at the end of year 10, resulting in an inverter cost that is higher than the one-time price at present. As the inverter production volume increases with an annual compounding rate of 30% and the inverter price decreases to 90% of the previous value per doubling, there can be 3.75 times doubling in 10 years and thus a price deduction of 33% (0.9^3.75= 67.4%). Thus the second inverter is bought at a price 33% lower in terms of current currency values. Adding up the hardware cost (modules and inverters), one time installation and annual maintenance-license cost, the cost of the whole system is estimated to be around US$1,397.7 K, which is around 2.01 million Singapore Dollars (SGD) based on the current exchange rate of 1.44 SGD per USD. The installed cost per Wp is $4.01, which is lower than current market value due to the zero loan financing assumption. The electricity cost is thus $0.173/kWh, which is around S$0.249/kWh. The calculation details are shown in Table 23.

HDB-Carpark Area	
Area(m2)	3870
Panel Area Percentage	90%
Available Panel Area (m2)	3483

Table 15: Summary of the Area Available for the HDB-Carpark Model

Solar Irradiation in Singapore	
Averaged Irradiance(w/m2)	1000
Daily Irradiation(kWh/m2)	4

Table 16: Summary of Solar Irradiation Characteristics in Singapore

Module Specifications	
Module Type	**FS-277**
Cell Efficiency	15%
Module Efficiency	10%
Vm(V)	69.9
Im(A)	1.11
Pm(Wp)	72
Area(m2)	0.72
Cost($/Wp)	0.98
Price($/Wp)	2.00
Warranty (Years)	25

Table 17: Specifications of Module FS-277 from First Solar

Power and Energy Calculations	
No. of modules	4838
Total Output Power(Wp)	277248.54
Total installed Power Rating (Wp)	**348300.00**
Total energy per day (kWh)	**1108.99**
Total Energy Per Year (kWh)	404782.87

Table 18: Power and Energy Available for a Carpark-HDB Model

Operation Specifications	
Operational Years	20
Interest Rate	1%
Discount Rate	99%
NPV Rate for operation years	18.05

Table 19: Summary of Operation Specifications

Invertor Specifications	
Life time (years)	10
Price Discount in 10 years (3 times doubling in 8 years)	0.67
Price ($/Wp)	0.35

Table 20: Summary of Inverter Specifications

System Efficiency Loss	
Module Rating Deviation	95%
Inverter Efficiency	95%
System mismatch efficiency	90%
Wiring Efficiency	98%
Total Efficiency (due to system loss)	80%

Table 21: Summary of System Efficiency Estimation

Maintenance and Licensing Cost	
Maintenance Cost per KW($/kW-yr)	50.51
Annual Maintenance Price($/year)	17592.59
Licensing cost ($/Year)	SGD 200/1.44= 138.89
Total Variable Cost	17731.48
NPC Cost over life time	319,974.29

Table 22: Summary of Maintenance and Licensing Cost

Cost Calculation		Percentage Cost
Module Cost ($)	696600.00	49.84%
DC/AC Inverter Cost ($)	204021.59	14.60%
Installation Cost ($)	177114.56	12.67%
NPV of Maintenance and Licensing Cost ($)	319974.29	22.89%
		100.00%
	USD-SGD	1.44
Total Cost (USD-SGD)	1,397,710.44	2,012,703.04
Installed Cost per watt (USD-SGD/Wp)	4.01	5.78
Electricity Cost (USD-SGD/kWh)	0.173	0.249

Table 23: Total Cost Estimation of a Grid-tied HDB-Carpark PV System

In terms of percentage cost as shown in Figure 29, the module cost is the highest part of cost that accounts for around 50%, which is similar with the currently installed PV systems as discussed previously. Again the next big component is the inverter cost which is 19% in this case. The relative high percentage of inverter cost signified the importance of reducing inverter cost next to reducing module cost as discussed in previous sections.

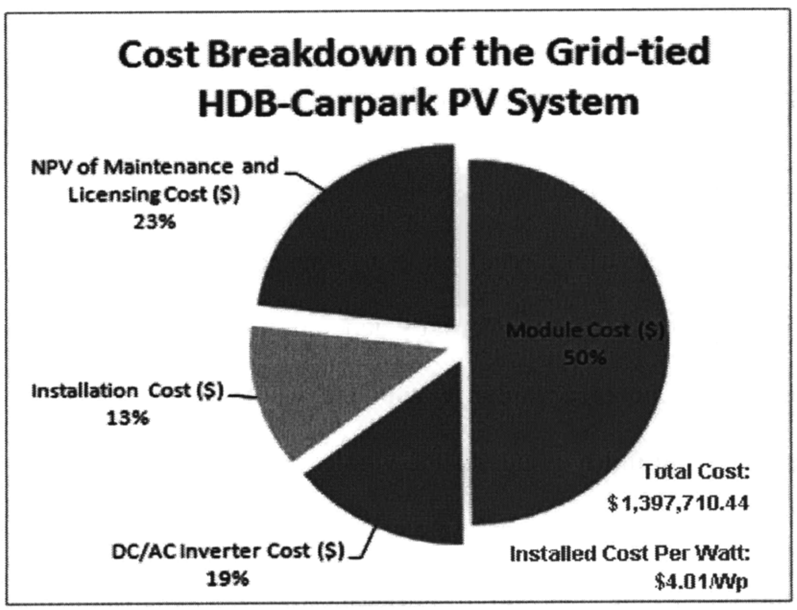


Figure 29: Relative Percentage Cost of a Grid- Connected HDB-Carpark PV System

If the system capacity is varied, as shown in Figure 30, the electricity cost will drop as capacity increases due to fix cost involved in the system such as the license fee. At small capacity, the cost electricity is very sensitive to capacity while it flattens out as the capacity increases above around 5MW. This trend is caused by economy of scale of the fixed cost.

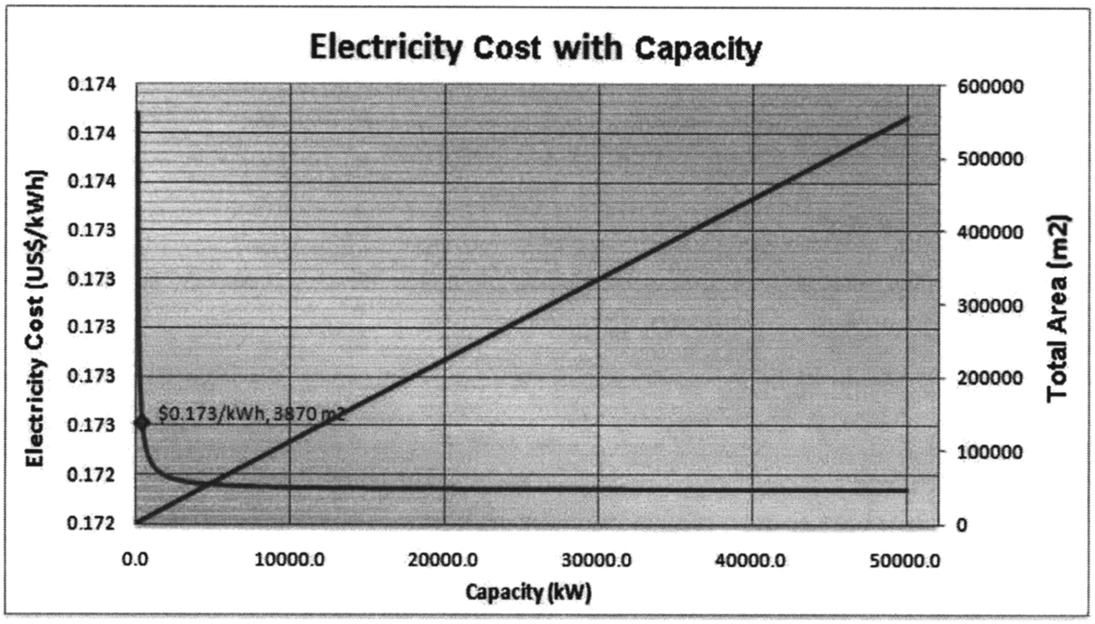


Figure 30: Electricity Cost of a Grid-tied System with Varying Capacity

b. Revenue and Profit Estimation

Currently, the utility electricity retail price in Singapore is S$0.170/kWh[92], which is around US $0.118/kWh. However, as an electricity generation system that sells electricity to the grid, the selling price shall be in accordance with the wholesale electricity price, which is generally lower than the retail utility price. As the wholesale price is revised every half an hour based on demand, the average value of wholesale price for the solar hours from 6am to 6pm for the latest time period of 15 June 2009 to 12 July 2009 is used. The data for the wholesale electricity price every half an hour for this period is taken from the Energy Market Company of

Singapore[1][93]. The average value is calculated as S$0.157/kWh or US$0.109/kWh, which is used to estimate the revenue of operating a solar system. As the LCOE from this grid-tied HDB-Carpark system is US$0.173/kWh, it is not market competitive with the utility price. As the yearly energy production is around 404,783 kWhs, the yearly revenue will be 63.55 thousand (404,783 kWhs x S$ 0.157/kWh) Singapore dollars or 44.13 thousand US dollars. Assuming an inflation rate equal to the interest rate, the future utility electricity price is assumed to be constant. Thus the total revenue over 20 years' operation is 20 times of the yearly value. Deducting the cost as presented before, the net profit will be negative or there is a net loss. The details are shown in Table 2.

	USD-SGD Exchange Rate	**1.44**
	USD	**SGD**
Total Cost	1,397,710.44	2,012,703.04
Revenue	882,426.66	1,270,694.39
Profit	-515,283.79	-742,008.65

Table 2: Revenue and Profit Estimation

b. Sensitivity Analysis of Profitability with Government Incentives and Cost Reduction

i. Government Rebate

As there is a net loss from this system, it is not considered as a good investment without government rebate. If considering government rebate, it is found that with 36.87% government rebate or the government offsets 36.87% of the initial cost, the investment will breakeven to begin to gain profit, as shown in Table 3. As the maximum government rebate in Singapore under the S$20 million Solar Capability Scheme described in Part 1[94] is 30-40% of the total cost which is capped at SGD 1 million and 36.87% of rebate of this grid tied HDB-Carpark

[1] http://www.emcsg.com

model is less than 1 million, the investment in this grid-tied HDB-Carpark PV system is able to breakeven with current state of government rebate.

	Government Rebate	36.8700%
	USD-SGD Exchange Rate	1.44
	USD	SGD
Total Cost	882,374.60	1,270,619.43
Revenue	882,426.66	1,270,694.39
Profit	52.05	74.96

Table 3: Government Rebate to Breakeven

However, to determine whether the investment is economically profitable, we have to compare the gain from this PV system with other type of investments. As the interest rate is assumed as 1%, an investment return of 1% is assumed for the Opportunity Cost[2]. Thus based on the capital investment of US$1.40 million or S$2.01 million, the Net Present Value (NPV) of the yearly return is US$252.22k or S$363.20k, as shown in Table 4. As just mentioned that without government incentives the system will bring a net loss and it can breakeven only with government rebate, a higher government rebate is required when opportunity cost is taken into account, as shown in Table 5. For the investment to be economically preferable, the government rebate has to be increased to 46.52%. As the maximum rebate is given as 40% of the total cost, this HDB-Carpark grid connected PV system cannot become an economical investment even with government rebate.

	USD-SGD Exchange Rate	1.44
	USD	SGD
Capital Investment	1,397,710.44	2,012,703.04
Interest Rate	1.00%	
Net Present Return Rate for 20 Years	18.05	
Net Present Return of Capital Investment	252,224.58	363,203.39

Table 4: Opportunity Cost Calculation

[2] Opportunity Cost= the Cost of the Second Best Alternative

	Government Rebate	46.5200%
	USD-SGD Exchange Rate	1.44
	USD	SGD
Total Cost	747,495.55	1,076,393.59
Revenue	882,426.66	1,270,694.39
Profit	134,931.11	194,300.80
Capital Investment	747,495.55	1,076,393.59
Interest Rate	1.00%	
Net Present Return Rate for 20 Years	18.05	
Net Present Return of Capital Investment	134,889.70	194,241.17
Net Economic Profit	41.41	59.63

Table 5: Government Rebate for Economic Profitability

ii. Government Grid Feed-in Price Tariff

An alternative form of government incentive is to set a higher buying price for the electricity sold into the grid, which is known as Feed-in Price Tariff. To make the PV system breakeven, the feed-in price shall be equal to the estimated electricity cost. To make the PV system economically profitable, the feed-in price shall be $0.204/kWh, which is around twice the current price of $0.109/kWh. The details are shown in Table 6.

	Feed-in Price Tariff	0.20381
	USD-SGD Exchange Rate	1.44
	USD	SGD
Total Cost	1,397,710.44	2,012,703.04
Revenue	1,649,975.94	2,375,965.35
Profit	252,265.49	363,262.31
Capital Investment	1,397,710.44	2,012,703.04
Interest Rate	1.00%	
Net Present Return Rate for 20 Years	18.05	
Net Present Return of Capital Investment	252,224.58	363,203.39
Net Economic Profit	40.91	58.92

Table 6: Feed-in Price Tariff for Economic Profitability

iii. Reduction of Hardware Cost

If government incentive is not considered, the cost of the PV system has to be reduced to make the system an economic investment. As the estimated LCOE is now $0.173/kWh without loan financing while the current utility wholesale electricity price is $0.109/kWh, the cost of the system has to be reduced by ($0.173- $0.109)/$0.173, which is 37.0%. It means that 37.0% of the total cost has to be removed. As the module cost itself takes 50% of total capital cost, thus the module price has to be reduced by 37.0%/50%, which is 74% from the current $2.00/Wp to $0.52/Wp.

c. Profitability with Consideration of Carbon Trading

One additional revenue source of a solar electricity generation system could come from participating in international carbon trading with its CO2 emission reduction amount. The carbon credit trading system present in some European countries works in a way that the party who reduces its CO2 emission will have more carbon credits to sell to those who need to emit more CO_2 than required by the government. In Singapore, the carbon intensity from the two largest power generation companies, Tuas Power [95] and Senoko Power [96] are used to estimate the mass of CO_2 emission when 1kWh electricity is generated from natural gas. Averaging the Senoko's carbon intensity in 2005 (450g/kWh) and Tuas' carbon intensity in 2006 (418g/kWh), the approximate carbon intensity for gas-generated electricity in Singapore is about *434g/kWh.*

As the current carbon trading price in Europe is ~$21.30/ton [97], the cost compensation from carbon trading can be calculated as 434g/kWh * $21.3/ton, which is around $0.0092/kWh. It means that the current carbon trading price can compensate around $0.0092/kWh of the electricity cost, reducing the current cost of $0.173/kWh to $0.163/kWh. And to make the carbon trading price able to compensate the difference between the current cost of $0.173/kWh and the utility wholesale electricity price of $0.109/kWh, a carbon trading price of ($0.173-

$0.109)/434g/kWh is required which is equal to $146.66/ton, which is around 7 times of the current trading price and around 3 times of the predicted trading price at 2016 (~$56.83/ton [98]), as shown in Figure 1.

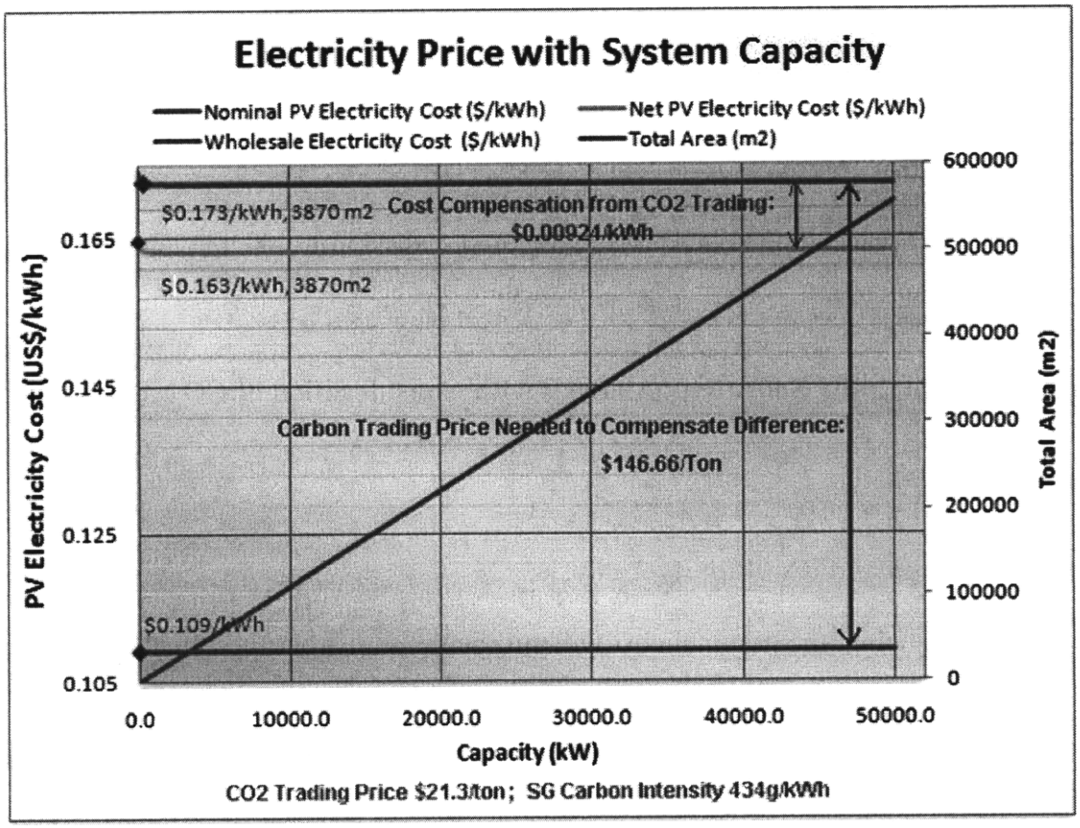


Figure 1: Electricity Cost with Consideration of CO2 Trading

If carbon trading is considered during the above profitability sensitivity analysis with government incentives and cost reduction, the relative requirement will be relaxed. The details are summarized in Table 1. "W/" represents "with" and "Max 40% to 1M SGD" represents the current government rebate policy under the S$20 million Solar Capability Scheme. The cells highlighted in yellow represent the feasible options that can be down to make the PV system breakeven or economically preferable. It can be seen that even with consideration of CO2 trading, the current government rebate is still unable to make the grid-tied HDB-Carpark Unit PV system an economical investment. The feed-in price tariff seems a more feasible option as the required price is less than 2 times of the current utility electricity price and the total generation capacity in Singapore is not to exceed 5% of the current grid capacity which is around 6GW[99].

Total Cost: $1,397,710.44;	**Installed Cost Per Watt: $4.01/Wp**		
Rebate to Breakeven	36.9%	31.6% w/CO2	Max 40% to 1M SGD
Rebate to be Economically Preferable	46.6%	42.0% w/CO2	Max 40% to 1M SGD
Feed-in Price to Breakeven	$0.173/kWh	$0.164/kWh w/CO2	S$0.236/kWh w/CO2
Feed-in Price to be Economically Preferable	$0.204/kWh	$0.195/kWh w/CO2	S$0.280/kWh w/CO2
Cost Reduction Requirement: (0.173 or 0.163 -0.109)/0.173=37.0% or 33.1%	Module price: Drop by 37.0/50 = 74.0% to $0.52/Wp : Drop by 33.1/50 = 66.2% to $0.68/Wp w/CO2		

Table 1: Profitability Sensitivity Analysis with Consideration of CO2 Trading

5.5.1.2 Evaluation with Loan Financing

a. Cost Estimation and Profitability Analysis

With loan financing, the nominal cost will still be the same, but the actual cost with loan financing will be the sum of the annual installment for 20 years discounted by the 1% discount rate. If 100% of capital cost is financed with bank loan at an interest rate of 10%, the total cost will go up to $2.96 million, which is more than twice of the capital cost in the case without loan financing. The electricity cost now is $0.366/kWh, which is more than twice as high as the previous cost of $0.173/kWh. The installed cost per Watt becomes $8.51/Wp, which is more than twice of the previous $4.01/Wp. With the same electricity selling price, the revenue from the system stays the same and the system now has a net loss of around $2 million. The details of estimation are shown in Table 2. The cost breakdown is shown in Figure 2, which is the same as the previous case since the loan financing is to the total capital cost rather than any component.

	USD-SGD Exchange Rate	1.44
	USD-SGD	1.44
Total Cost (USD-SGD)	1397710.44	2012703.04
Annuity for 20 Years	164174.54	236411.34
Net Present Value of Actual Total Cost	2,962,620.44	4266173.43
Installed Cost Per Watt (USD-SGD/Wp)	8.51	12.25
Electricity Cost (USD-SGD/kWh)	0.366	0.527
Revenue	957,264.53	1,378,460.93
Profit	-2,005,355.90	-2,887,712.50

Table 2: Cost Estimation with 100% Loan Financing

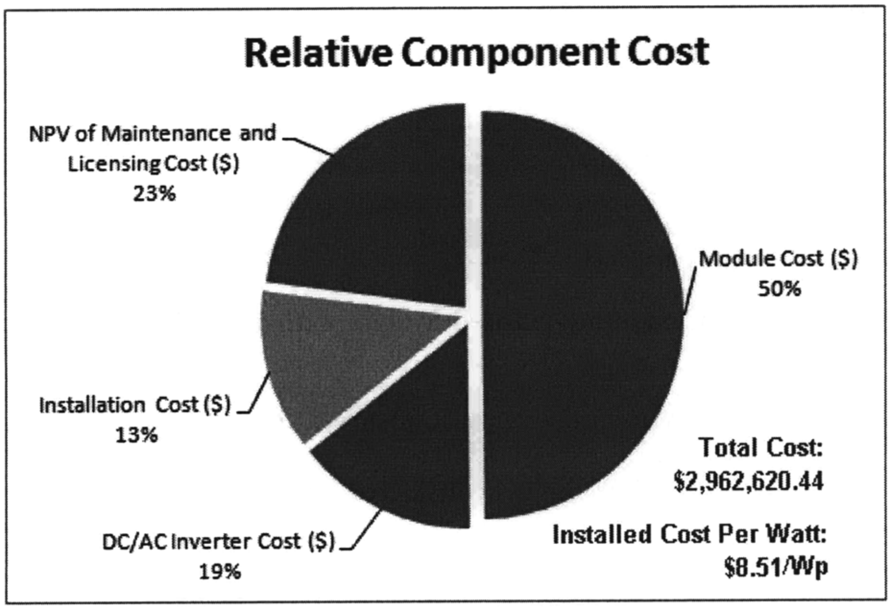


Figure 2: Cost Breakdown of a Grid-tied System with 100% Loan Financing

Similarly with before, when the electricity cost is plotted against system capacity, a similar curve with electricity cost reducing with increasing capacity is derived, as shown in Figure 3. The shape of the curve is resulted from the same economy of scale.

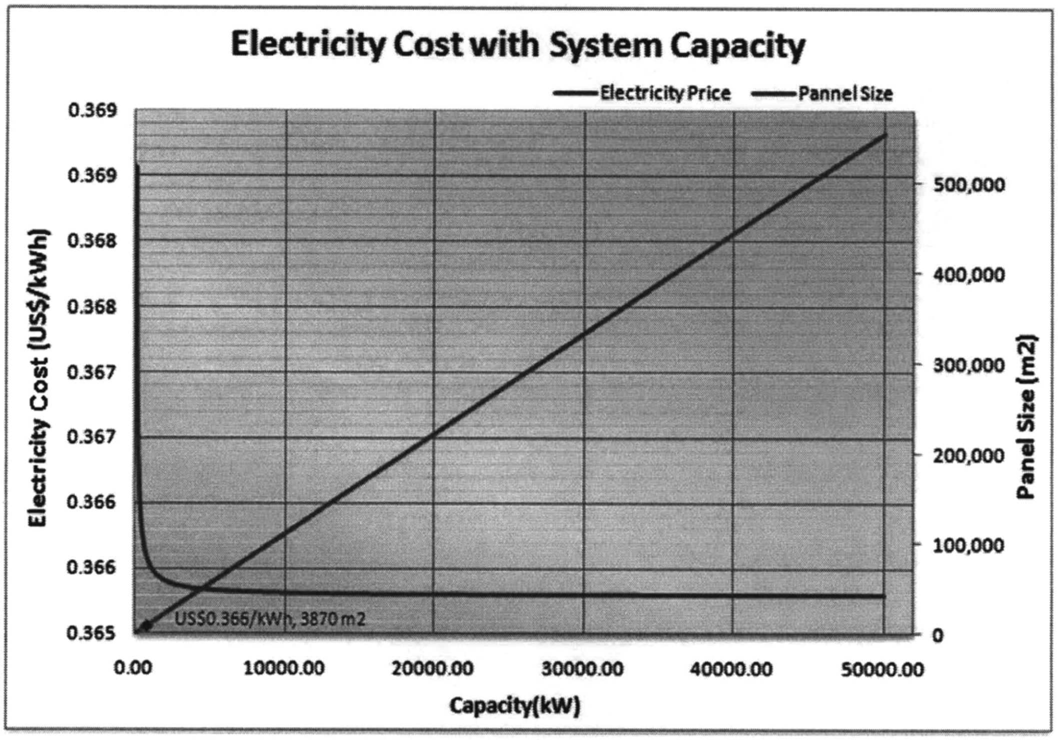


Figure 3: Electricity Cost of a Grid-tied System with 100% Loan Financing

b. Profitability Sensitivity with and without Consideration of Carbon Trading

Similarly with before, if CO2 trading is considered, the current trading price will only be able to account for a cost reduction of \$0.0092/kWh. Without any government incentives, the CO2 trading price has to be increased to \$592.17/ton (\$0.366- \$0.109)/kWh/(434g/kwh) in order to compensate the difference between the estimated electricity cost and current utility wholesale price.

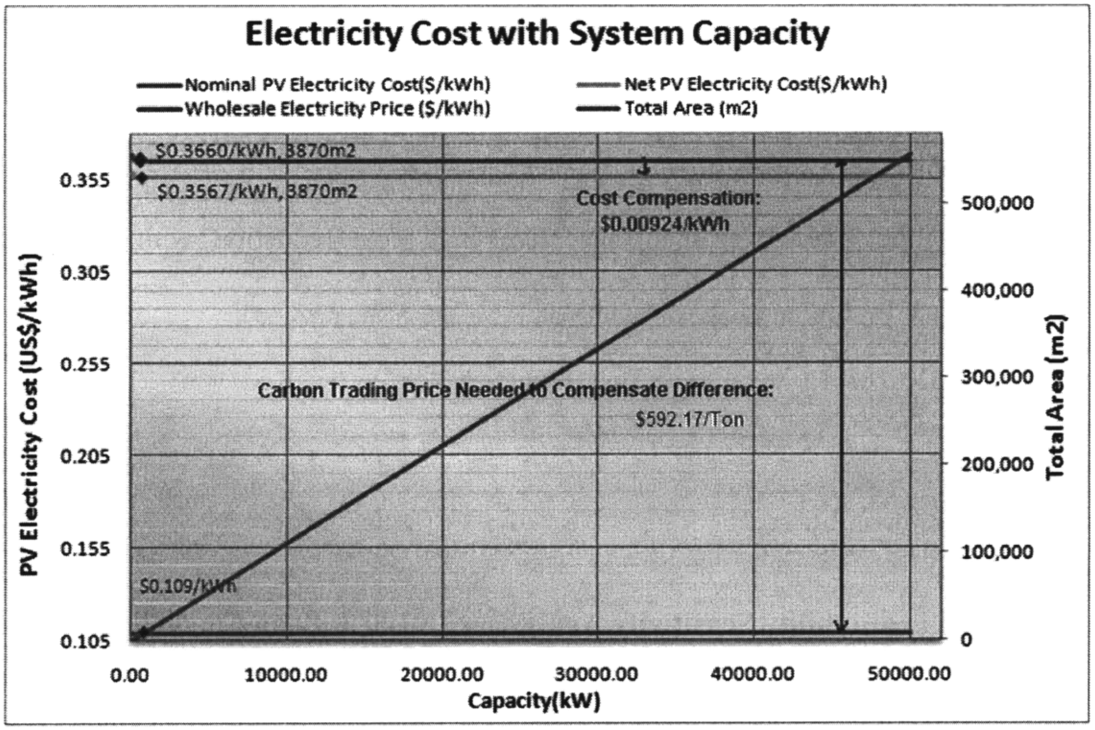


Figure 4: Electricity Cost of a Grid-tied System with 100% Loan Financing and Consideration of CO2 Trading

In this case with a higher net loss from the system, government incentives are again necessary to make the investment breakeven. With a higher capital cost, the government rebate required to breakeven is now 70.3%, which exceeds the maximum available rebate. If CO2 trading is considered, the rebate required is still 67.7%. Thus the current state of government rebate of 40% is not able to make the investment breakeven.

If feed-in price incentive is considered, the breakeven price will be the same with the cost of $0.366/kWh. If CO2 trading is considered, the price required will drop by $0.009/kWh to $0.357/kWh, which is more than 3 times of the current utility wholesale electricity price of $0.109/kWh.

Without any government incentive, the capital cost has to be reduced by 70.2% to make the electricity cost drop to the utility price of $0.109/kWh. If CO2 trading is considered, the requirement is still 69.5%. As the cost of modules and the cost of inverters together account for around 69% of the total capital cost, even when both of their prices are reduced to 0, the system is unable to breakeven.

The details about the government incentives and cost reduction with and without consideration of carbon trading are listed in Table 6.

Total Cost: $2,962,620.44;	**Installed Cost Per Watt: $8.51/Wp**		
Rebate to Breakeven	70.3%	67.7% w/CO2	Max 40% to 1M SGD
Feed-in Price to Breakeven	$0.366/kWh	$0.357/kWh w/CO2	S$0.514/kWh w/CO2
Cost Reduction Requirement: (0.366 or 0.357 -0.109)/0.173= 70.2% or 69.5%	Module and Inverter Cost (69%) drop to 0 → cannot breakeven		

Table 3: Profitability Sensitivity Analysis with 100% Loan Financing

5.5.2 Private House Model

5.5.2.1 Evaluation without Loan Financing

a. Cost Estimation and Profitability Analysis

As estimated in section 5.4.2, the total available area of a private house is 340 m^2 for the horizontal roof area and 392.6 m^2 for the tilted roof area. As the panels shall have an inclination of 15° for optimal solar irradiance capture, the total available horizontal irradiation area is 340m^2 and the actually panel area is 352 m^2 area.

Based on the typical household electricity consumption of 3.56kWh per day, we can first estimate the area needed to supply so much energy from the PV system per day. With the Singapore irradiation data of 4 hours peak irradiation at 1000W/m^2, the maximum PV power required is 3.56kWh/4hours, which is 890.0 Watt peak. Considering the 80% system efficiency and 72Wp per module, we can calculate the number of modules required is 15.5. By rounding up to the nearest whole number, 16 modules are required to offset the electricity consumption of the household. With 16 modules, the total amount of solar electricity generation is 3.67kWh and the installed power rating is now 1152.0Wp. Again based on a 90% percent overhead area, the area required to generate the amount of required electricity can be estimated, which is around 12.8 m^2. As the total available area is around 340 m^2, it is technically feasible to install such as system. The details are shown in Table 4.

The operational assumptions of this system will be the same with that described in **Error! Reference source not found.** and the module specifications are as described in **Error! Reference source not found.**. As now the peak power of the system is around 1kWp, which belongs to the small system category, the higher inverter price of \$0.72/Wp will be used. Similarly with before, the annual maintenance cost is only \$58.2/Wp for a small system. The electricity generation license cost are taken as the same with the previous model, as described in **Error! Reference source not found.**.

PV System Size Estimation	
No. of modules	16.0
total output watt peak	917.5
total rating of watt peaks(Wp)	**1152.00**
total energy consumption per day (kWh)	**3.67**
Total Energy Per Year (kWh)	1339.55
Panel Area Percentage	90%
Installation Area Required(m2)	**12.8**

Table 4: System Size Estimation to Offset Electricity Bills for a Private House Model

The total cost of the system is estimated to be at US\$7.83k or S\$ 11.28k. The electricity cost is around US\$0.292/Wp or S\$0.421/Wp. The calculation details are shown in Table 5.

Cost Calculation		Percentage Cost
Module Cost ($)	2304.00	29.41%
DC/AC Inverter Cost ($)	1388.16	17.72%
Installation Cost ($)	585.83	7.48%
NPV of Maintenance and Licensing Cost ($)	3556.39	45.39%
		100.00%
	USD-SGD	1.44
Total Cost (USD-SGD)	7834.38	11281.51
installed cost per watt (USD-SGD/Wp)	6.80	9.79
Electricity Cost (USD-SGD/kWh)	0.292	0.421

Table 5: Relative Percentage of Various Cost of a Grid- Connected PV System

In terms of percentage cost as shown in Figure 5, the module cost is not the largest part of cost component any more due to the relative small system size. Instead, maintenance and licensing cost now takes about 45% of the total cost. This is because of the high annual cost of obtaining two licenses, which can take 37% of the total cost even if maintenance cost is considered negligible. Also as the inverter price for small systems is higher, the short lifetime of inverter makes its cost again stay at a high percentage of total cost.

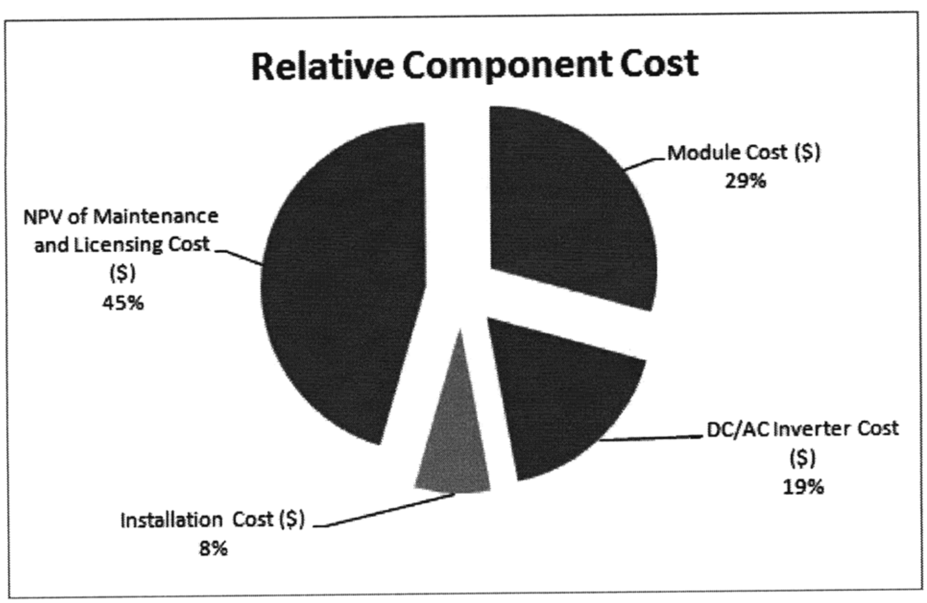


Figure 5: Relative Percentage Cost of a Grid- Connected Household PV System

As the current retail electricity price is \$0.118/kWh, the PV electricity cost of \$0.292/Wp is more than twice as high as grid electricity price, which makes such a system non-economical without government rebate. If we look into the calculations of the revenue and profit, we will again see a net loss from this investment, as shown in Table 6.

	Government Rebate	0.0000%
	USD-SGD Exchange Rate	1.44
	USD	SGD
Total Cost	7834.38	11281.51
Revenue	3162.83	4554.47
Profit	-4671.56	-6727.04

Table 6: Revenue and Profit Estimation

b. Profitability Sensitivity with and without Consideration of Carbon Trading

If CO2 trading is considered, the electricity cost can be reduced by \$0.0092/kWh from \$0.292/kWh to \$0.283/kWh with the current CO2 trading price, which is still more than twice of the current utility retail electricity price of \$0.118/kWh. In order to compensate the difference between the cost of \$0.292/kWh and the electricity price of \$0.118/kWh, the CO2 trading price has to be increased to \$401.90/kWh.

From the profit estimation, the net loss indicates the necessity of government incentives. If considering government rebate, the investment will breakeven when the government rebate is more than half at 59.7% of the system cost. If CO2 trading is considered, the rebate required is still 56.5%. Thus the current state of government rebate of 40% is not able to make the investment breakeven. For the system to be economically preferable or a better investment than its 1% return alternative, the rebate requirement is 65.9% without consideration of carbon trading and 63.2% with consideration of carbon trading, which are further out of the practical rebate limit.

If feed-in price incentive is considered, the breakeven price will be the same with the cost of \$0.292/kWh. If CO2 trading is considered, the price required will drop by \$0.009/kWh to \$0.283/kWh, which is more than 2 times of the current utility retail electricity price of \$0.118/kWh. To make the system economically preferable, the price has to be increased to \$0.346/kWh without consideration of CO2 trading or \$0.337/kWh with consideration of CO2 trading.

Without any government incentive, the capital cost has to be reduced by 59.6% to make the electricity cost drop to the utility price of \$0.118/kWh. If CO2 trading is considered, the requirement is still 56.4%. As the cost of modules and the cost of inverters together account for around 48% of the total capital cost, even when both of their prices are reduced to 0, the system is unable to breakeven.

The details of the above analysis are shown in Table 7.

Total Cost: \$7834.38;	**Installed Cost Per Watt: \$6.80/Wp**		
Rebate to Breakeven	59.7%	56.5% w/CO2	Max 40% to 1M SGD
Rebate to be Economically Preferable	65.9%	63.2% w/CO2	Max 40% to 1M SGD
Feed-in Price to Breakeven	\$0.293/kWh	\$0.284/kWh w/CO2	S\$0.409/kWh w/CO2
Feed-in Price to be Economically Preferable	\$0.346/kWh	\$0.337/kWh w/CO2	S\$0.485/kWh w/CO2
Cost Reduction Requirement: **(0.292 or 0.283 -0.118)/0.292= 59.6% or 56.4%**	Module and Inverter Cost (48%) drop to 0 → cannot breakeven		

Table 7: Profitability Sensitivity Analysis of a grid-tied Private House Model without Loan Financing

5.5.2.2 Evaluation without Loan Financing

From the previous analysis, it has been shown that a private house PV model needs a capital funding of around USD7.8K or SGD11.3K, which is generally less than one month's household income for households that reside in private houses (SGD12,570[79]), Thus the loan funding case will not be considered.

5.6 Electricity Cost of Stand-alone System

With a battery storage cost around the same with module cost, the stand-alone PV system is always more costly as compared to grid-tied systems. As we have mentioned, the grid-tied system will always be considered whenever possible. As Singapore is a highly industrialized city state which has excellent infrastructure and grid connectivity, the stand-alone system is not necessary for general electricity generation. Thus the stand-alone models in Singapore will not be considered due to its non practicality and non economic feasibility.

6. Summary

In the previous sections, the PV system based solar electricity generation has been evaluated based on a review of the state of the art solar cell technologies. The three generations of solar cell technologies have been evaluated based on their efficiency, cost and reliability characteristics. Commercial CdTe modules from First Solar Ltd. were found to have the best efficiency to cost ratio, making them the best module choice in land-scarce and tropical Singapore. Thus based on a standard 77.5 Wp module FS-775 from First Solar, two models, one on an HDB apartment roof and the other based on a private house, have been developed to estimate the cost of PV electricity and to evaluate the economic feasibility of PV systems in Singapore .

With the fact of high storage cost and Singapore's island-wide grid coverage, grid-tied PV systems are more cost effective and thus have been investigated and reported in detail. The HDB unit model which consists of the area of 4 HDB blocks and 1 auxiliary Car Park is considered as a large system with a capacity larger than 70kW and it has the lower electricity cost as compared to small private house model due to price discount of the inverter, which takes about 20 to 30% of the total cost of a grid-tied PV system. Also at the current stage of technical development, the cost of electricity from the relatively large scale PV system, the HDB unit system, is about US$0.173/kWh or SG$0.249/kWh, which is the lowest cost possible without any government incentives and loan financing. Yet it is not market competitive with the current electricity wholesale price of US$0.109/kWh or S$0.157/kWh. Government incentives such as government rebate and Feed-in Price Tariff were also evaluated. It is found that a government rebate of around 36.9% is required to make the system breakeven while a government rebate of 46.6% is required to make the system an economically preferable investment as compared with its next best alternative of 1% interest return. With the current available maximum government rebate of 40% capital cost capped at 1 million Singapore Dollars, the grid-tied HDB block PV system is found to be able to breakeven but cannot become an economically profitable investment. If Feed-in Price Tariff is considered, the system can be a profitable investment at a price 2 or 3 times higher than the current utility electricity price. If without any government incentive, the module price has to drop to around \$0.52/Wp to make the system breakeven. When the carbon trading is used to compensate the electricity cost, the current carbon trading price has to be increased by 7 times of the current price to be able to compensate the difference between the estimated cost of electricity and current utility electricity price.

For the private house model, it is found that even with the maximum 40% government rebate, it is still not advisable for Singapore private house owners to install PV systems. Even when the cost of modules and inverters drop to 0, the system is still unable to breakeven.

If the current price of carbon trading is taken into consideration, the various electricity cost reduction scheme can be slightly relaxed, but the conclusions will not change.

Thus in Singapore, in order to make solar electricity from PV systems competitive with current utility electricity, the current option is to provide a one-time funding from the government to build the PV system and at the same time set a Feed-in Price Tariff for solar electricity. But more opportunities of PV system will arise in the future when the hardware cost of the PV system such as modules and inverters can be reduced substantially, and/or the utility electricity price rises due to fossil fuel depletion, and/or CO2 trading price increases due to the growing global environmental concern.

Part 3: Modeling Solar Energy Based Electric Vehicle System

1. Introduction

Based on the reviews of Electric Vehicles (EVs), Solar Thermal and PV Systems, and Flow Battery Storage, we as a group will investigate the feasibility of implementing XEV transportation systems based on solar electricity in this chapter. Four different models will be built and evaluated, namely the Battery Swapping Model, the PHEV Private Car Model, the standalone Carpark PV System Charging Model with Energy Storage and the Grid-tied PV-EV System model.

The battery swapping model is designed for taxis. In this model, battery electric vehicle (BEV) is selected as the best car model for taxi transport in Singapore. Battery swapping stations will be built to support the operation of BEV taxis. The economic feasibility and environmental benefits of this model will be assessed.

PHEV was evaluated to be the best car model for private transportation. In this section, we will analyze the economic impact of PHEV to private consumers. In both battery swapping model and PHEV model, the electricity charged to the battery is directly drawn from the utility.

The standalone Carpark PV System Charging model with Energy Storage will be evaluating a charging station that is based on a standalone PV system built on the roof of a shopping mall carpark, where PHEVs can be charged with solar electricity. The economic feasibility and environmental benefits will be evaluated followed by respective suggestions to the government in assisting the clean energy policy making.

The Grid-tied PV-EV System is to evaluate the feasibility of building a large-scale grid-connected PV system which could provide clean electricity to the grid, from which Electrical Vehicles can be charged. The price competitiveness and environmental benefits of solar electricity from such as system will be evaluated, again followed by suggestions to the government in assisting relative the policy making.

2. Battery Swapping Model

2.1 Background

Battery Electric Vehicle (BEV) is an important player in the green vehicle market. BEV is equipped with a large battery and thus able to drive a long distance purely relying on electric power. The optimized battery design is capable for a driving distance of 100 miles per charge. Its average driving speed of 31 miles per hour also fits to Singapore' traffic condition well—the average driving speed in Singapore is around 39 miles per hour in expressways and less than 17 miles per hours in artery roads[100]. Moreover, BEV emits no CO2 and produces much lower noise than conventional internal combustion engine vehicle [101].

In addition, a smooth running of BEV systems requires the building of battery swapping stations. The battery swapping stations allows BEV drivers to switch a depleted battery to a fully charged one in a long trip. In a battery swapping station, BEV drivers enters a lane covered with a conveyor. The conveyor will move the car automatically and align the car with battery swapping platform. At this platform, a depleted battery will be taken out from the bottom of the car and replaced with a fully charged one. The depleted battery is then shifted to a store room for charging. After charging, this battery will be available for the next driver. This battery exchange process will be done in a fully automatic way and takes only a few minutes. Since the average daily driving distance of taxis is about 260 miles in Singapore, battery swapping stations must be built to support a smooth running of BEVs, which can drive for only 100 miles per charge [102]. Fortunately, Singapore has excellent infrastructure for building swapping stations, such as robust electric grid, compact urban environment, and advanced IT services [103]. With the support of swapping stations, BEV could travel over long distance and maximally demonstrate its merit of low operating cost.

Therefore, it is believed that BEV is one ideal candidate for creating an environmental friendly taxi system in Singapore.

2.2 Objective

A proposed BEV taxi model is developed from the perspective of a taxi company. In this model, we assume that the taxi company needs to replace 1250 old taxis with new cars. This company has two choices—it can either buy 1250 gasoline cars or 1250 BEVs. A detailed cost model will be built for both choices to assess the economic impact to the taxi company. In particular, for the BEV taxi system, we assume the taxi company will build and operate battery swapping stations.

2.3 Economic Analysis

A simple model is built to assess the feasibility to develop the BEV plus battery swapping station system in Singapore.

2.3.1 Swapping Stations

In this model, it is assumed that BEV will take 5% market share in the taxi segment, or about 1250 taxis in Singapore will be switched from gasoline cars to BEVs in the next five years. Note the number of taxis was 24,446 in Singapore in 2007 [104].

Four battery swapping stations will be built to support BEVs. The driving distance per charge for BEVs is only 100 miles. Taxi drivers need to exchange batteries for 2.5 times on average per day. Battery swapping stations are built to provide this service.

However, swapping batteries does not necessarily create many troubles for taxi drivers. Firstly, currently drivers need to refuel two times daily. In general, in Singapore two drivers share a cab and each of them will take in charge of the cab for twelve hours daily. They will refuel the cab before passing it to the other colleague. On the other hand, swapping a battery takes less than one minute [105]. Swapping batteries for 2.5 times daily actually does not increase drivers' refueling time. Secondly, the driving distance to battery swapping stations is very short. This distance is approximately 5 Km (3.125 miles) on average. As shown in Figure 6, four stations will be built in the west, north, east and downtown area of Singapore, at the locations marked by stars. With these stars as centers, four circles with a radius of 10 Km (6.25 miles) are drawn on the map. This figure shows than almost every corner of Singapore is well covered by these four swapping stations. In the worst scenario, taxi drivers need to travel 10 Km to reach the swapping station. However, considering the overlapped areas among the four circles and random distribution of taxis with areas covered by these circles, it is expected that the average distance between a taxi and a battery swapping station is only about 5 Km.

Well establish power grid in Singapore is also able to support the potentially high power demand from these battery swapping stations. In our model, the worse case happens when all 1250 BEV batteries starts to charge simultaneously. This total demand is still less than 61 MW (each BEV battery has charging power of 48.73 kW). In contrast, the total installed capacity of power plants in Singapore is about 9775 MW and current peak demand is only approximately half of that. Please refer to chapter 1 of this report for more details about the energy market in Singapore.

2.3.2 Cost Assumptions

The projected cost for constructing a battery swapping station is US$500,000 according to Better Place's estimation [105]. This station is designed to swap batteries, recharge depleted batteries in an entirely automatic process. Drivers even do not have to walk out of the car.

During the initial trial period, we estimate that the north, east and west stations will each serve 20% of BEVs, while the downtown station takes care of the rest 40% BEVs.

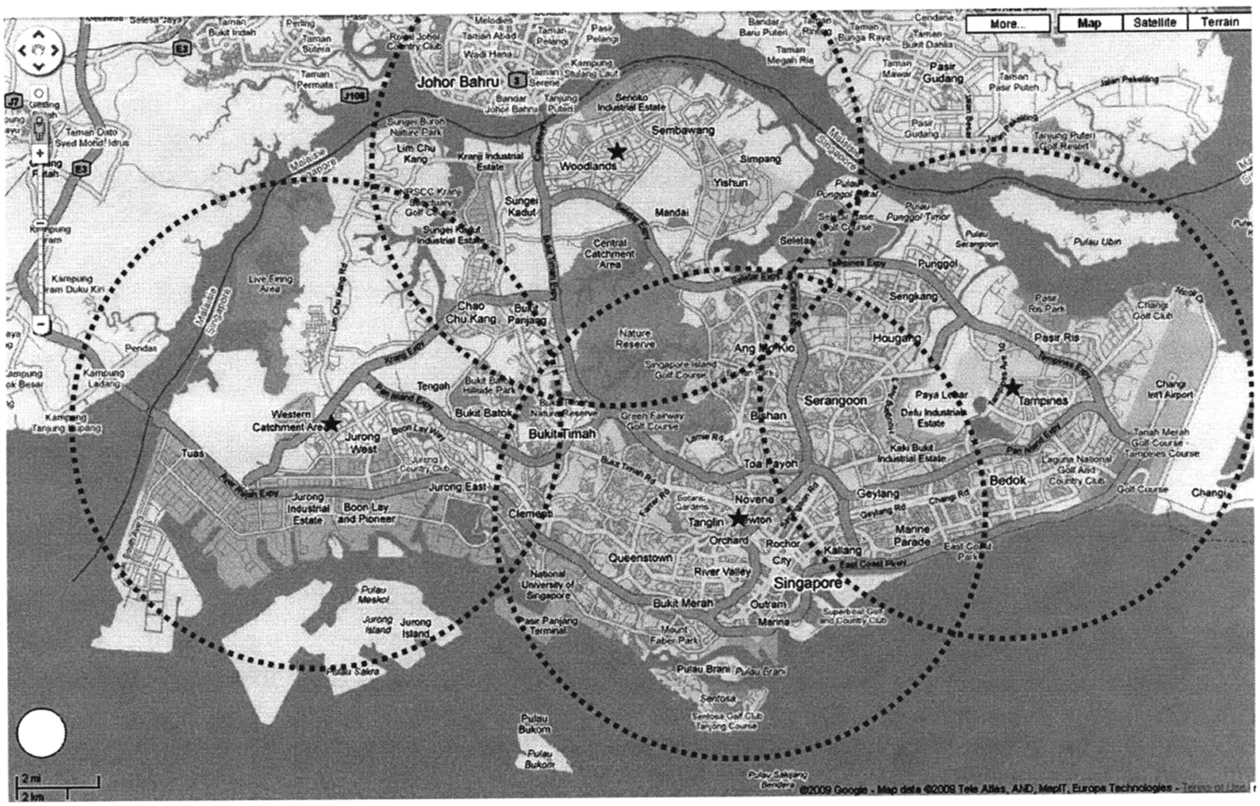


Figure 6: Battery Swapping Stations in Singapore

Another major cost for this BEV model is the additional batteries. In our calculation, three batteries (including the one in use in the car) are prepared for every BEV taxi. They are able to support the taxis to continuously drive for 10 years. Each battery costs about US$18,138 (excluding other taxes). However, this cost can be offset at least partially from the long term saving in gasoline.

Other assumptions in our model include:

Taxis are sequentially released every day, so that they go back to charging stations roughly sequentially to avoid long time queuing during battery swapping.

The operation and maintenance cost is US$60,000/year for the downtown station and U$50,000/year for the rest stations.

A fully changed BEV battery can store 37 kWh of electrical energy and support the BEV for a 100-mile driving distance. For BEV and its battery specifications please refer to H. Fu's thesis of Assessment of Lithium Ion Battery Technologies.

The average electricity price from year 2005 to year 2009 is calculated to be $0.0931/kWh in Singapore[106] and this price is used in our calculation.

The average taxi daily mileage in Singapore is 258 miles[107].

The average gasoline price from year 2005 to year 2009 is calculated to be $1.86/gallon including tax in Singapore[103] and this price is used in our model.

Another gasoline car, Toyota Crown with fuel efficiency of 21 mpg[108] and upfront cost of $26,058[109], is selected in comparison to BEV during the calculation of their operation costs.

BEVs enjoy Green Vehicle Rebate, which is 40% of vehicle open market value OMV at registration. All vehicles are subjected to registration fee, COE and other fees. Please refer to Chapter 1 for more details about car policies in Singapore.

7% of GST tax is applied to all commodities in our model.

2.3.3 Cost Analysis

Based on these assumptions, the operation cost for BEVs is calculated and summarized in Table 8. The cost per mile of BEVs is approximately $0.22.

Swapping Station Infrastructure Cost	$2,000,000.00
BEV Cost	$64,687,500.00
Vehicle cost	$31,250,000.00
Vehicle GST	$2,187,500.00
Green Vehicle Rebate	($12,500,000.00)
Registration fee	$31,250,000.00
COE & Other fees	$12,500,000.00
Number of Battery Pack	$3,750.00
Battery Pack Cost with GST	$73,500,975.00
Total BEV and Battery Cost	$138,188,475.00
Operation Cost	$180,000.00
Electricity cost	$2,392,297.60
Maintenance cost	$250,000.00
Total Variable Cost	$2,822,297.60
Annual interest rate	10%
Infrastructure life time (year)	20
BEV and battery life time (year)	10
Annual Infrastructure Amortization	$234,919.25
Annual BEV & Battery Amortization	$22,489,537.93
Annual Fixed Cost	$22,724,457.18
Annual Variable Cost	$2,822,297.60
Total Annual Cost	$25,546,754.78
Total Annual Cost per Car	$20,437.40
Cost per Mile for a BEV	$0.217

Table 8: Cost of Battery Swapping Model for BEVs

The cost breakdown of BEV system is shown in Figure 7: Cost Breakdown of BEV **System**. It is noticed that the annual infrastructure amortization, which account for the infrastructure cost of battery swapping stations, is only about 1% of the annual BEV & battery amortization. It is also noticed that the major contribution in variable cost is from electricity bill. The first fact means that the cost for building supporting infraction for BEVs is far smaller than that of BEVs and their batteries in our model. Infrastructure does not play a significant role, once the population of BEVs reaches a certain size, say 1250 in our model. Moreover, both facts further indicate that a higher penetration rate of BEVs into the taxi markets does not necessarily bring down much of its cost per mile, because the cost for BEVs is mainly from cars, their batteries and electricity bills.

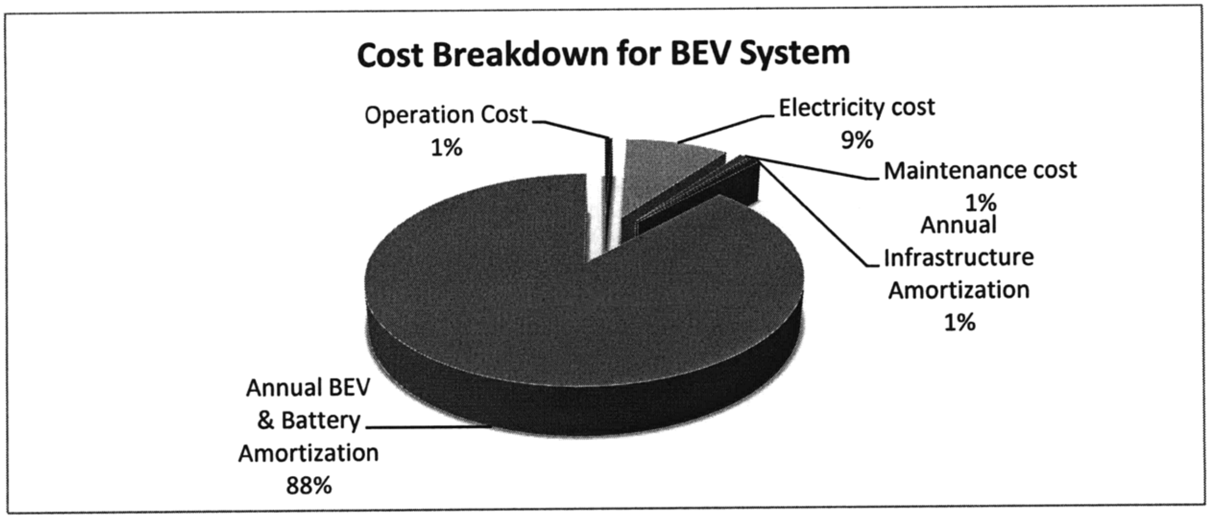


Figure 7: Cost Breakdown of BEV System

By assuming the gasoline price of \$1.86/gallon, we also calculated the cost per mile for gasoline cars. This price is \$0.199 as shown in Table 9.

Toyota Crown Taxi	\$63,940.06
Vehicle cost	\$26,058.00
Vehicle GST	\$1,824.06
Registration fee	\$26,058.00
COE & other fees	\$10,000.00
Toyota Crown Amortization	\$10,405.95
Fuel Efficiency (mpg)	21
Gasoline Price (\$/gallon)	\$1.860
Daily gasoline consumption (gallon)	\$22.85
Daily Operation Cost	\$8,340.77
Annual Operation Cost	\$8,340.77
Annual gasoline consumption (gallon)	
Total Annual Cost for Gasoline Car	\$18,746.72
Cost per Mile for Gasoline Car	\$0.199

Table 9: Cost of Gasoline Cars

From above calculations, it can be seen that BEV taxis are not economically sound as compared to gasoline taxis. The cost per mile for BEV is about $0.02 or 9% more expensive than that of gasoline taxis. This is mainly due to expensive BEV batteries.

However, this conclusion changes as gasoline prices rises, which is very likely to happen in the next ten years. Further sensitivity analysis on the system cost with gasoline price is provided below.

First, the relationship between gasoline and electricity prices in Singapore is analyzed. We have calculated the monthly average price of both gasoline and electricity (wholesale electricity price) in Singapore from 2005 to 2009 [110] [111]. The electricity price is converted into U.S dollar at the ratio of US$1=S$1.44. These data are plotted in Figure 8. From this figure, it is found that electricity retail price is very closely linked to the gasoline price in Singapore. Therefore, we assume a linear relationship between these two prices in our model. This means that as the gasoline price rises, the electricity tariff will increase for the same percentage. The reference prices are set based on the average prices in the past five years. They are $0.093/kWh for electricity and $1.86/gallon for gasoline.

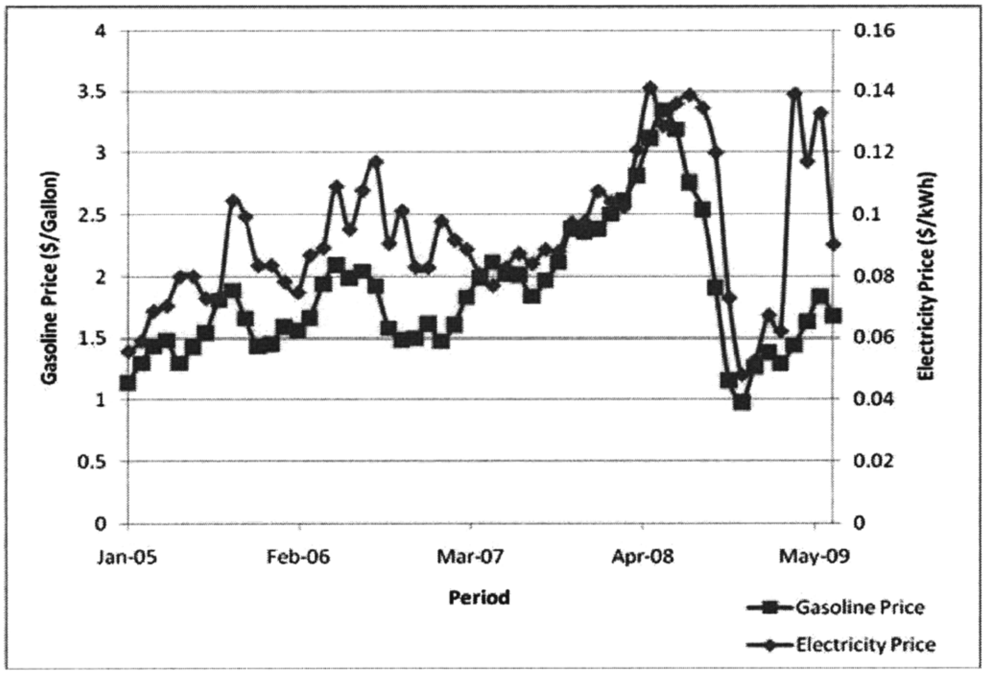


Figure 8: Monthly Average Prices of Gasoline and Electricity in Singapore

The cost per mile for both BEV and gasoline cars are calculated and plotted in Figure 9. As can be seen from this figure, as the fuel cost rises, gasoline car's cost per mile ramped up rapidly. The electricity tariff also increases with the gasoline price. However, since the electricity bill is only a small portion in the overall cost of BEVs, this increase does not bring a significant change in the cost per mile for BEVs.

As can be seen from Figure 9, the breakeven price for BEVs and gasoline cars occurs at gasoline price of about $2.4/gallon. This means that BEVs will be more economically competitive in terms of cost per mile, once the fuel price goes above $2.4/gallon.

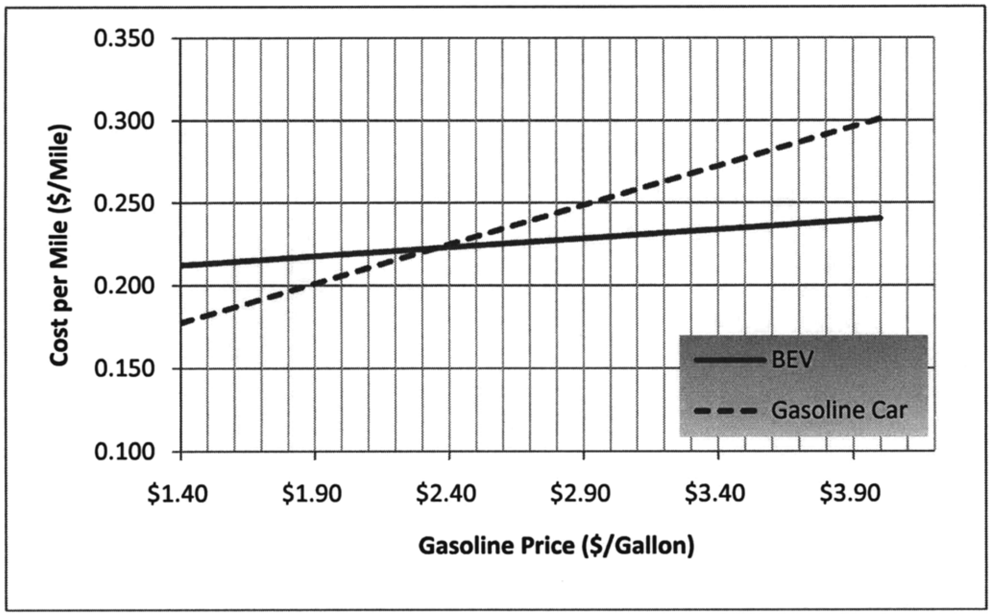


Figure 9: Cost per Miles for Gasoline Cars vs. Gasoline Price

2.3.4 Environmental Analysis

From environmental perspectives, BEV taxis are highly preferred for less CO_2 emission. In order to quantify the environmental benefits of BEV taxis, the total amount of CO_2 emission in 10 years are estimated for both kinds of taxis.

The main source of CO_2 emission for BEV taxi is from electricity generation. Amount of CO_2 emitted during electricity generation can be calculated based on the following assumptions:

(1) Average transmission loss from power station in Singapore is estimated to be 1.5%[31]

(2) Average CO_2 emission during power generation is 434g/kWh in Singapore (refer to chapter 1 for more details of Singapore power generation)

(3) Estimated CO_2 emission for gasoline taxi is 371.2g/mile based on the data given by Felix Kramer[112].

	CO2 emission

	(kg/mile)
BEV taxi	0.09548
Gasoline taxi	0.3712235
BEV taxi CO2 reduction	0.2757435

Table 10 shows that by operating BEV taxi, 0.27kg/mile of CO_2 reduction can be achieved compared with its gasoline counterpart. The total CO_2 reduction for a single BEV in one year (assuming daily driving distance of 258 miles) can be as high as about 25 tons. In our model, 1250 BEVs will be deployed. This would mean a total of nearly 31.3 kilo tons of CO_2 reduction yearly. Here we assume the electricity is generated from power plants relying on natural gas as fuel. If this electricity is from renewable energy, the CO_2 reduction can go up to 0.371 kg/mile or an annual saving in CO_2 reduction of nearly 35 tons per car.

	CO2 emission (kg/mile)
BEV taxi	0.09548
Gasoline taxi	0.3712235
BEV taxi CO2 reduction	0.2757435

Table 10: CO2 emission of BEV and Gasoline Taxis

In order to reduce CO_2 emission and promote BEV taxi system in Singapore, incentives must be given by Singapore government. Based on the previous cost analysis, a price of $70.21/ton of CO_2 emission is needed so as to make BEV taxi at the same cost level of gasoline taxis, at present gasoline and electricity prices ($0.093/kWh for electricity and $1.86/gallon for gasoline). In comparison, according to the CO_2 price established by European Union's Emissions Trading Scheme (EU ETS), current CO_2 is charged at $21.3/ton[113], and it will increase further to $56.86 by 2016 in Europe. Therefore, either more government incentives or higher carbon tax are needed for the implementation of BEV taxi system in a near term. However, as oil prices and environmental concerns rise in the future, it is highly likely that BEV taxis will be running in Singapore streets.

3. Private Car Model

3.1 Background

According to Land Transport Authority (Singapore), the average daily mileage of private cars is 35.4 miles[107]. As shown in Fu's model, under current technical standard, Plug-in Hybrid Electric Vehicle (PHEV) has a driving distance of 40 miles by operating in electric mode. This is enough to cover the entire daily mileage of a private car user. While the operation cost and CO_2 emission for PHEV and BEV are quite similar, PHEV has a much less upfront cost compared to BEV. Therefore, PHEV is chosen to target at private car market in this Private Car Model.

3.2 Assumptions

By applying the same topology as in BEV battery swapping model, economic and environmental impacts of PHEVs are assessed based on following assumptions:

(1) Average daily mileage of a private car is 35.4 miles.

(2) Gasoline and electricity prices are $1.83/gallon and $0.0932/kWh respectively.

(3) PHEVs enjoy Green Vehicle Rebate, which is 40% of the vehicle's open market value (OMV) at registration.

(4) All vehicles are subjected to registration fee, COE and other fees.

(5) 7% of GST tax is applied to commodities.

(6) A fully charged PHEV can drive for 40 miles in electric mode. After that, it operates as a hybrid electric vehicle (HEC) with a fuel efficiency of 50 mpg.

(7) A gasoline car with a fuel efficiency of 26.4 mpg is used for comparison.

3.3 Cost Model

The result is summarized in Table 11. As shown in this table, although PHEV has a higher upfront cost than gasoline car, drivers could making savings from its lower operating cost.

Nevertheless, a negative net present value in Table 11 indicates that this saving is not large enough to offset the high upfront cost of a PHEV. As a result, at current electricity and gasoline prices, it is not cost effective for a consumer to purchase a PHEV.

PHEV cost	$73,972.69
PHEV OMV price	$38,307.00
PHEV GST	$2,681.49
Green vehicle rebate	($15,322.80)
Registration fee	$38,307.00
COE & other fees	$10,000.00
Gasoline car cost	$56,212.75
Gasoline car OMV price	$22,325.00
Gasoline car GST	$1,562.75
Registration fee	$22,325.00
COE & other fees	$10,000.00
PHEV initial investment	$17,759.94
PHEV operation cost	$0.82
Gasoline operation cost	$2.49
Daily PMT(saving)	$1.67
Annual PMT(saving)	$610.21
Net present value	($11,657.82)
PHEV CO2 emission (kg/day)	3.87736
Gasoline car CO2 emission (kg/day)	12.3192
PHEV CO2 reduction (kg/day)	8.44184

Table 11: Implementation Cost of PHEV vs. Gasoline Car

From environmental perspectives, operating a PHEV can achieve 8.442 kg of daily CO_2 reduction than running a gasoline car. In order to make PHEV as cost competitive as a gasoline car, the charge of $378.3445/ton on CO2 emission is required to bridge this cost gap. This price is as high as 17.5 times of the current CO_2 trading price ($21.6/ton) in the European Union. Therefore, at this moment PHEV is not likely to be adopted as private cars.

The sensitivity of NPV to gasoline is also analyzed. The same relationship between gasoline and electricity price as in Battery Swapping Model is used. Figure 10 shows the change of NPV as gasoline price increases. It is observed that PHEV will not be profitable unless the gasoline price goes to as high as about \$5.4/gallon. Based on the historic trend of gasoline price in Singapore, this price is not likely to occur in the short run.

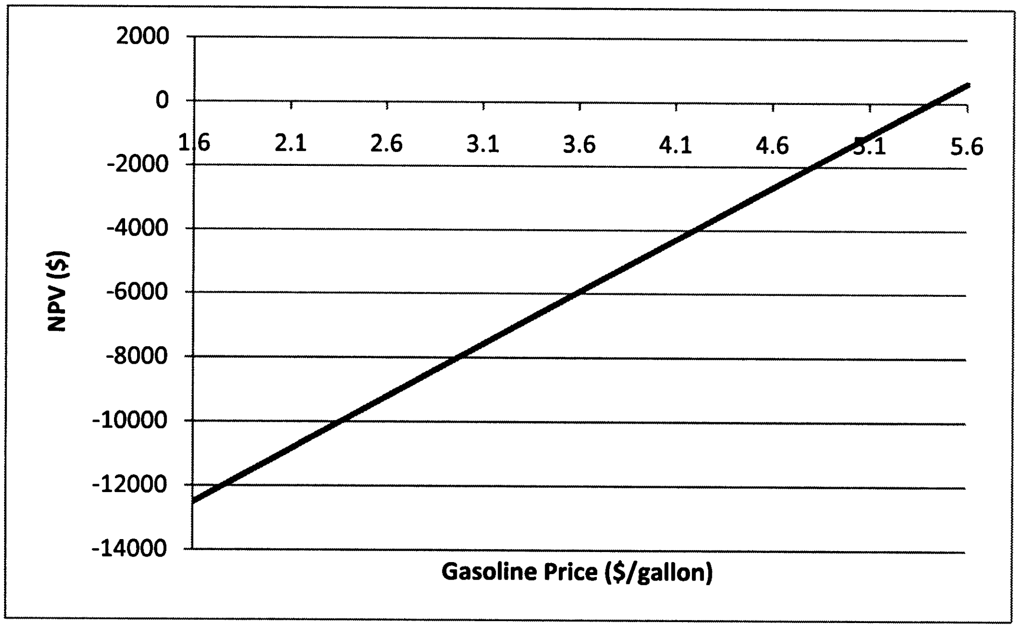


Figure 10: NPV vs. Gasoline Price

As the driving distance becomes longer, PHEV's merit of low operation cost becomes more significant. Sensitivity of CO_2 breakeven price with varying daily mileage is shown in Figure 11. This figure suggests that PHEV is probably a good choice for users of higher daily mileage, such as postman.

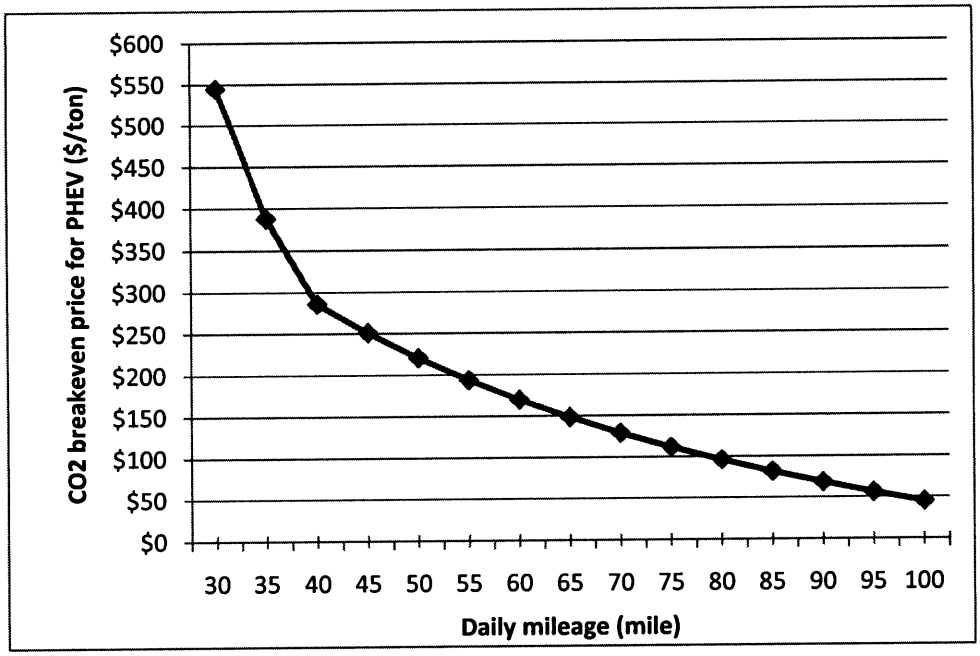


Figure 11: CO2 Breakeven Price with Varying Daily Mileage

4. Car Park Charging System Model

4.1 Background

In order to help expedite the penetration of electric vehicles (EV) into the private car market in Singapore, supporting infrastructures for EV should be built at the frequently and easily accessible areas with dense population of cars. One of the most important infrastructures is the charging system.

Singapore has limited land, so its city planning does not allow much space for private parking. Aggregated public cars parks are commonly seen around the island, at both residential and commercial areas. The residential areas in Singapore mainly comprise of tall flats, and separate multi-storey buildings are usually built for car parking for the residents in the region; it is also very common to see aggregated large-scale shopping complexes in Singapore, and the parking spaces are usually located within the same building. Therefore, providing charging spots at those parking areas can help alleviate EV users' worries of running out of "fuel", while they are resting at home or shopping with families for the weekends.

In order to make EVs even "greener", solar energy technology should be leveraged for the greater benefit to the environment. This is because solar energy is the only viable clean energy resource for electricity generation in Singapore, as being discussed in *Report 1*. Solar thermal technology and solar PV technology are separately evaluated by Liu and Sun in their respective thesis. According to Liu, solar thermal technology is not suitable for electricity generation in Singapore due to its low efficiency in a highly diffusive radiation environment, like Singapore [1]. Therefore, solar PV technology is chosen for evaluation in this car park model.

[1] According to Liu, to make it economically sound, solar thermal power plant requires a minimum daily direct normal isolation of 6 kWh/m2. However, due to more than 40% of diffusive radiation, the daily DNI in Singapore is less than 3 kWh/m2. Moreover, solar thermal power plant requires a vast area for solar field. This further prevents it from entering the Singapore market, when the density of population is ranked number 2 in the world.

Furthermore, to fully capitalize on the solar energy available only during sunny daytime, energy storage system should be implemented together with the PV panels to make the solar energy even available for charging at night or during cloudy days. Moreover, energy storage system can eliminate the intermittent nature of electricity generation from solar PV.

4.2 Objectives

The ultimate aim of this Car Park Charging System (CPCS) model is to evaluate the profitability of building a Standalone Solar Electricity Generation System with Energy Storage (SSEGS-ES).

The final cost of electricity in $/kWh generated from the SSEGS-ES system (*P1*) will be compared with the current utility electricity price (*P2*) and the equivalent electricity price for the conventional combustion engine vehicles (*P3*). Based on the comparison, EV users' acceptance level and the future market of CPCS can be analysed. Correspondingly, possible policies and acts can be proposed to the government to incentivise such a system.

4.3 Assumption

There are a few important assumptions for building such an implementation model:

(1) The solar PV technology is based on the one evaluated in Sun's thesis. The capital cost of building such a solar PV panel is also obtained from the cost model in that thesis. The energy storage system makes use of the vanadium redox flow battery system (VRB) evaluated in Chen's thesis, likewise for its capital cost modeling.

(2) The specifications of EV batteries and charging parameters are obtained from Fu's thesis on EV battery evaluation. Based on his thesis, Plug-in Hybrid Electric Vehicle (PHEV) is believed to be the most suitable model for private car users in Singapore, because of its relatively

low overall cost in $/mile and sufficient driving range for private car users in Singapore. Herein, PHEV is used together with SSEGS-ES for the implementation model.

(3) The CPCS is assumed to be continuously operational for twenty years from its commissioning.

(4) An initial capital investment is used to build the entire CPCS, including the solar PV panels, VRB storage system and the auxiliary components. The balance-of-plant is included in the individual systems, and the final operation and maintenance (O&M) cost for the entire CPCS is incorporated into the initial capital investment. This lump-sum capital investment is taken from a bank loan with annual borrowing rate of 5%. The loan is paid back with equal annual installment for the next twenty years.

(5) The installed CPCSs is purchased by and owned the operators of the car parks, who can be the owners of shopping complexes and the neighborhood communities of the residential areas. They will charge the EV users for charging their vehicles during parking. This constitutes income for the CPCS owners who can use it to repay the bank loan for the next twenty years. The interest rate is assumed to be constant at 1% for the next twenty years, and the inflation rate is assumed to be zero in Singapore for this period.

4.4 Cost Model

4.4.1 Car park

The car park used in this model is the one used in one of the largest shopping complexes in south-western Singapore, the IMM shopping mall. Its outlook is shown in Figure 12 [114], respectively. IMM is purposely chosen for this model, because it is located between the downtown area and the rural suburbs, its accessibility and traffic amount can reasonably approximate the average standards in Singapore.

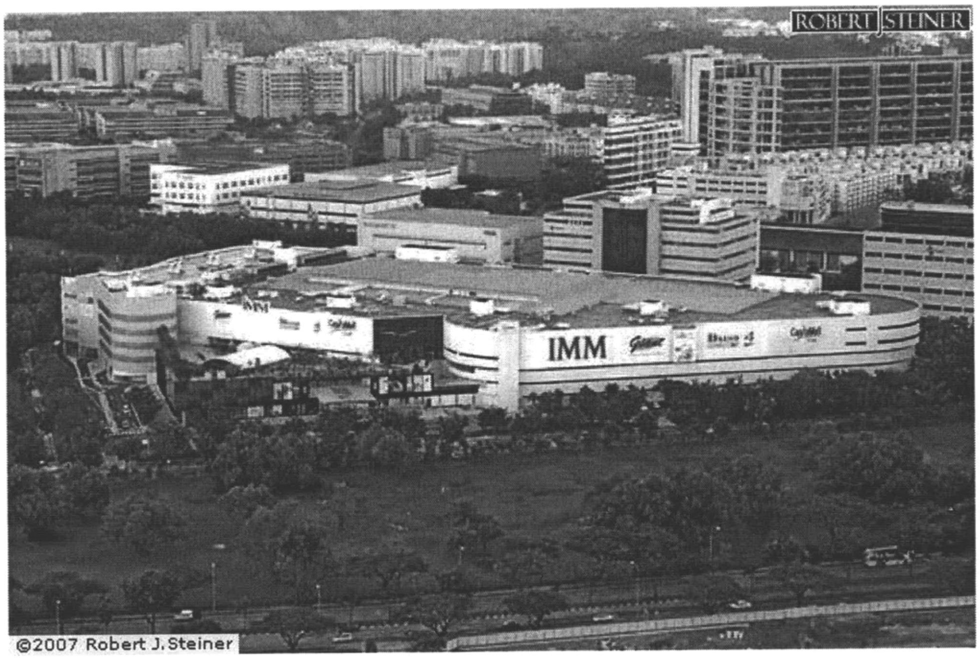


Figure 12: Outlook of IMM Shopping Complex

The roof-top area of IMM building is estimated to be about 37,810m^2, and there are about 1,300 car park lots available inside [115]. This is another reason for choosing IMM for the SSEGS-ES implementation, and more details will be presented in later sections.

4.4.2 Solar PV panels

Based on Sun's model of solar PV panels, it is assumed that 90% of the roof-top areas can be covered with PV panels, which is equivalently 37810×90%=34,029m^2. Assuming 90% of the roof-top areas are covered with solar PV panels, so that the total number of PV modules needed is about 51,250, each taking up an area of 0.72m^2. The solar PV panels are made from Cd-Te module from First Solar®. The important parameters and final capital cost of the solar PV panels are shown in Table 12. The total capital cost for the entire solar PV panels is about

$8,497,825.83. The breakdown of this total amount is shown in Figure 13. It can be seen the PV module cost amounts to more than 70% of the total cost.

Solar PV Panel	
Total area availble for PV panel (m2)	34,029.00
Total number of PV modules	47,262.50
Overall energy efficiency of PV module	88%
Total watt peaks (Wp)	3,009,694.91
Total electricity generated from PV panels per day (kWh)	12,038.78
Total electricity generated from PV panels per year (kWh)	4,394,154.56
Total PV module cost ($)	$6,019,389.81
Total capital cost of PV panel system ($)	$8,487,825.83
Capital cost per unit Watt peak ($/W)	$2.8202
Capital cost per unit energy ($/kWh)	$0.0966

Table 12: Important parameters and final capital costs of the solar PV panels installed for car park in the IMM shopping hall

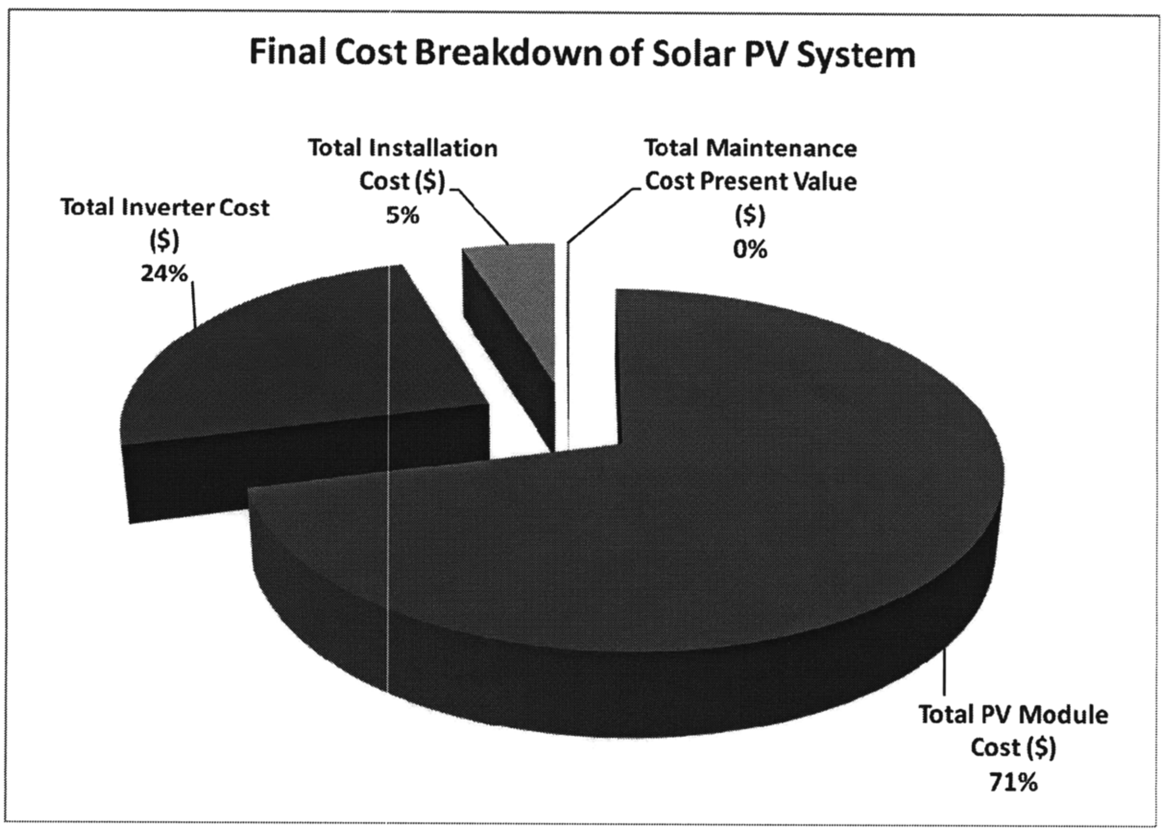


Figure 13: Final Cost Breakdown of the Entire Solar PC System

4.4.3 PHEV specifications

The PHEVs are driven by advanced Li-ion batteries which can be plugged into any normal power socket that provided 240V AC power supply.

Based on Fu's model of Li-ion batteries and reference [116], the charging characteristics PHEV batteries are shown in Table 13. The charging efficiency is assumed to be 90%; based on Chen's model of VRB system, the overall energy efficiency (input/output) is about 75%. The total electricity available for charging PHEV batteries is therefore calculated to be about 9,029kWh per day, and the number of PHEV batteries that can be fully charged is about 923 per day. This is smaller than the total parking lots available (about 1,300). Assuming that all the 923 PHEVs are plugged-in and charged from the VRB system at the same time, the maximum power capacity requirement for the VRB system hence is about 2.462MW.

PHEV	
Total electricity generated from solar PV panels per day (kWh)	12,038.78
Overall efficiency of VRB system	75.00%
Total electricity available for charging PHEV batteries (kWh)	9,029.08
Battery energy capacity (kWh)	8.8
Battery charging efficiency	90.00%
Number of PHEV fully charged per day	923
Battery charging AC voltage (V)	240
Battery charging current (A)	7.5
Battery charging power (kWh)	1.8
Battery charging duration to fully charged (hours)	4.89
Total maximum charging current in a day (A)	10,260.32
Total maximum charging power in a day (kW)	2,462.48

Table 13: Important parameters for PHEV batteries

4.4.4 Capital cost of VRB storage system

The VRB system will be constructed in the proximity of the IMM building. A computerised control system will be installed to dynamically control the charging and discharging dynamically of VRB system. The electricity will be generated with intermittence from the solar PV panels at sunny daytime, and then it can be supplied to the charging spots throughout the car park inside the IMM building at anytime of the day.

From the previous section on PHEV specifications, the total maximum charging power required from the VRB system is about 2.462MW. A 100kW safety margin is added to the maximum power output of VRB system, resulting in 2.562MW. The discharge duration is estimated to be 4 hours, resulting in a total energy capacity of 10,240kWh of the VRB system which is larger than the required total electricity for charging 923 PHEVs fully per day, 9,029kWh (highlighted in yellow in Table 13). Hence, the final purchase price of the entire VRB system is *\$3,213.098.06* for a 2.562MW VRB system with discharge duration of 4 hours. Based on Chen's model, the final capital cost per cycle is about \$0.0836/kWh. A summary is shown in Table 14.

VRB Storage System	
Output Power Capacity (kW)	2,562
Discharge Duration (hours)	4
Total energy capacity (kWh)	10,248.00
Capital cost per unit power (\$/kW)	\$548.50
Capital cost per unit energy (\$/kWh)	\$134.65
Fixed cost (\$)	\$135,800.00
Total capital cost (\$)	\$2,920,998.23
Total purchase price (\$)	\$3,213,098.06
Capital Cost per Cycle (\$/kWh)	\$0.0836

Table 14: Important specifications and final purchase price of the VRB storage system

Figure 44 shows the breakdown of final cost of the entire VRB system. Due to the large power and energy capacity of the power plant, the fixed cost component only constitutes about 2% of the total cost, whereas the cell stacks and the vanadium electrolyte amounts to more than 55%.

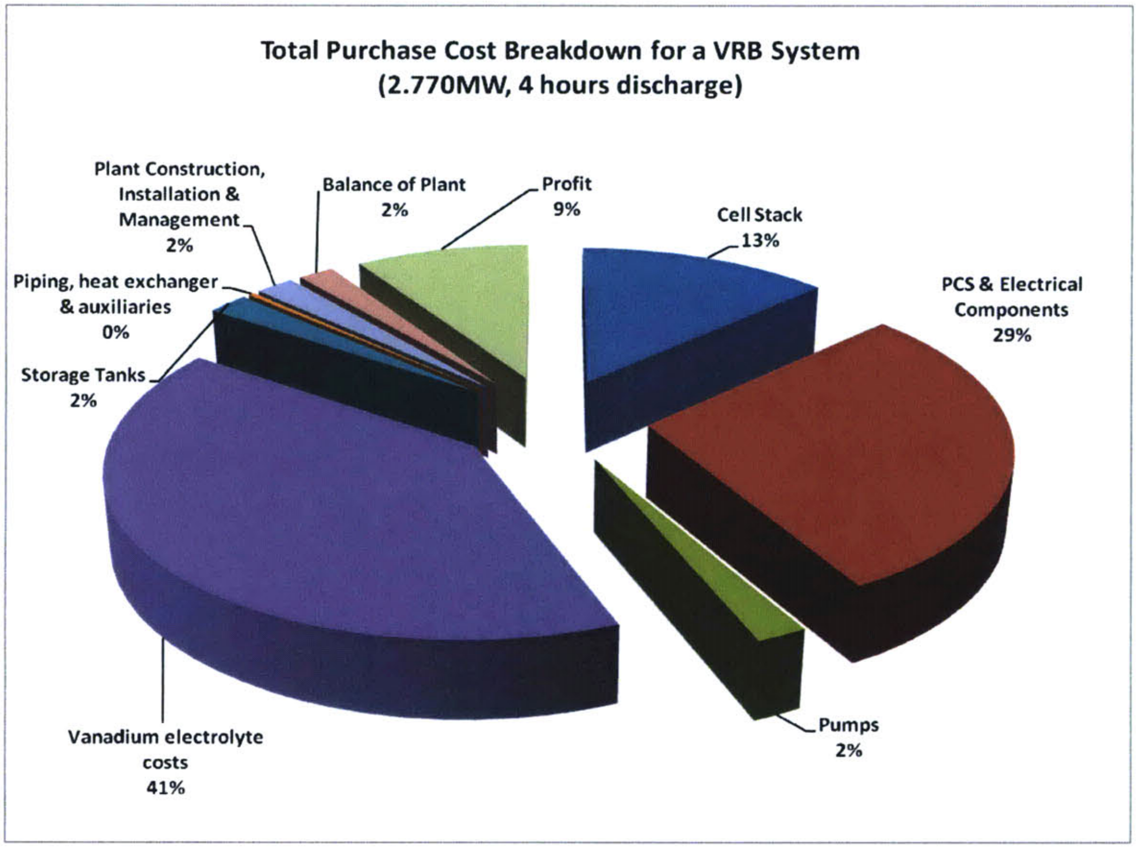


Figure 44: Final cost breakdown for VRB system with 2,770kW with 4 hours discharge duration

4.4.5 O&M cost of the CPCS

Since in both Sun's cost model of solar PV panels and Chen's cost model of VRB system, the O&M costs are included in the final capital costs, there is no separate O&M cost associated with the CPCS system.

4.4.6 Final cost of electricity output from CPCS, P1

Based on the previous discussion, the total initial capital cost amounts to *$11,700,923.89* in total. Figure 45 shows the final cost breakdown: VRB system costs about 27% and the solar PV system takes up the remaining 73%.

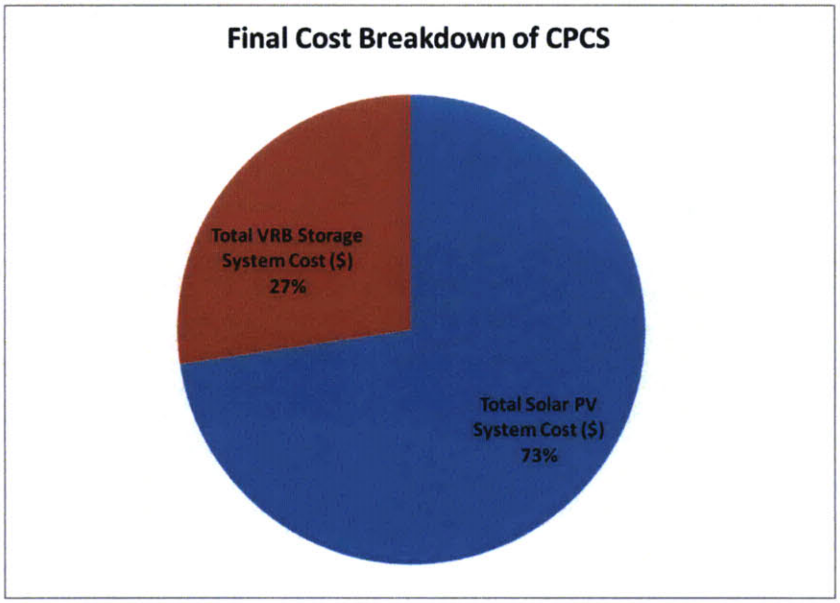


Figure 45: Final cost breakdown of the CPCS system installed in IMM building

It is assumed that this amount is loaned from a local bank with borrowing rate of *5%*, with payback period of 20 years of equal annual payment. Hence, the annual instalment is *$938,912.41*.

Electricity from the CPCS is sold the EV user. Once they plug-in their PHEV onto the wall-plug in the car park, the power meter installed beside the charging spot will start to calculate the total charging cost. The cost of electricity for the next twenty years is assumed to be constant.

In order to find the break-even electricity price (denoted as *P1)*, the annual income from electricity sale must be equal to the annual loan payment. This is calculated to be *$0.2849/kWh*. Table 43 shows the important parameters for this calculation.

Calculating Break-even Electricity Price from CPCS ($/kWh)	
Total initial capital investment ($)	$11,700,923.89
Average interest rate	1%
Electricity output from VRB per day (kWh)	9,029.08
Number of CPCS's operating days per year	365
Total electricity supplied from CPCS per year (kWh)	3,295,615.92
Life cycle of CPCS (years)	20
Cost of electricity to EV users ($/kWh)	$0.2849
Annual revenue ($)	$938,912.41
Total bank loan ($)	-$11,700,923.89
Annual bank loan rate	5%
Loan payback period (years)	20
Equal annual installment for loan payment ($)	$938,912.41
Annual cash inflow ($)	$938,912.41
Annual cash inflow ($)	$938,912.41
Annual net cash flow ($)	$0.00
NPV of net cash flow in 20 years ($)	$0.00

Table 15: Calculation of the break-even electricity price for the next twenty years

Therefore, the final break-even electricity retail price from the CPCS at IMM building should be ***P1 = $0.2849/kWh.***

4.5 Model Analysis

4.5.1 Utility electricity price, P2

The yearly average electricity price from 2005 to 2009 is shown in Table 16. The average electricity price during this period is $0.0932/kWh, and this is taken as a reference of the expected average electricity retail price in the next twenty years. Hence, ***P2 = $0.0932/kWh***. This is about third (~32.7%) of *P1*.

Year	Electricity Price ($/kWh)
2005	$0.0775
2006	$0.0929
2007	$0.0884
2008	$0.1128
2009	$0.0943
Average	$0.0932

Table 16: The yearly average electricity price in Singapore from 2005 to 2009

4.5.2 Sensitivity Analysis – Car Park Roof-top Area

Figure 16 shows that *P1* decreases with car park roof-top area and approaches towards about $0.275/kWh when the roof-top area goes to very large. This "asymptotic" value is about 3 times of the average utility electricity price (shown as the red line in Figure 16), and about 2 times of the highest historical utility electricity price in the past five year shown in Figure 16. The vertical dotted line represents the case of CPCS built on IMM building.

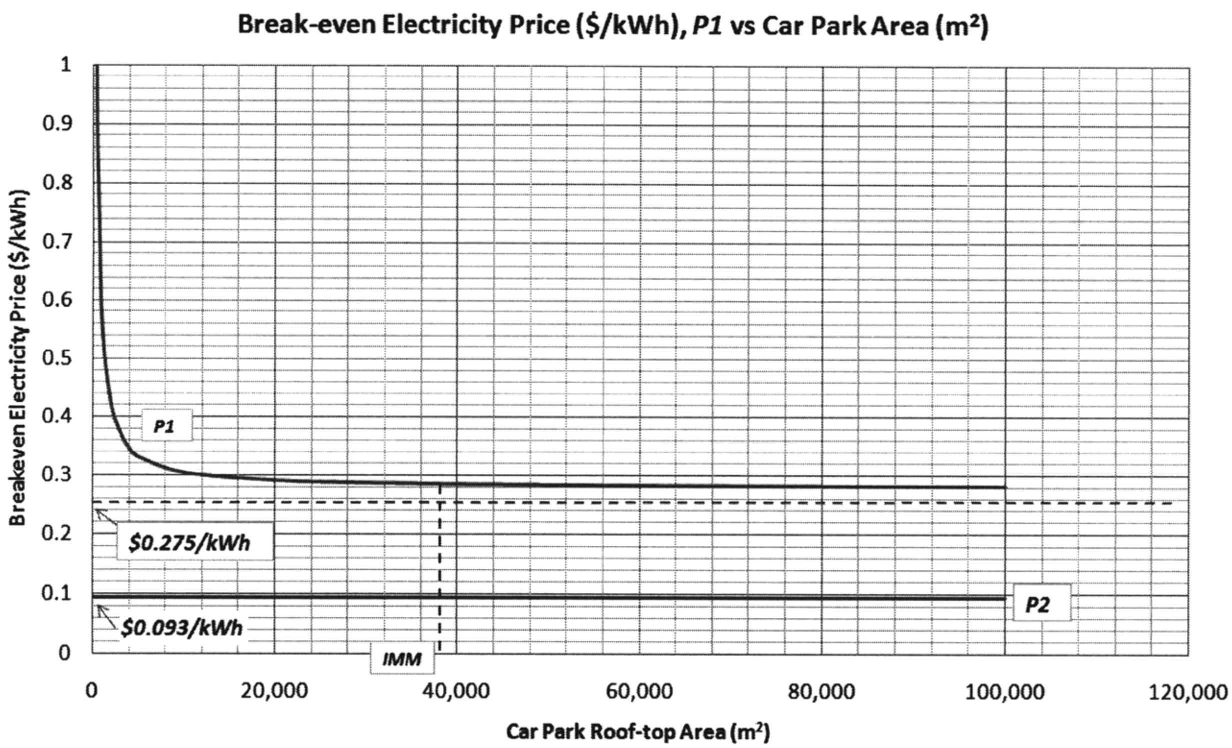


Figure 16: Variation of break-even electricity price from CPCS (P1, $/kWh) against car park area (m^2) and utility electricity price (P2, $/kWh)

The initial quick decrease in P1 with increasing car park roof-top area is due to the relatively large portion of capital investment in building CPCS even when the amount of electricity generated from the PV panels is very limited. This can be seen from Figure 18 which shows comparison of increasing rates of total cost of CPCS and annual electricity generation capacity, with respect to the roof-top area, as well as the increasing rates of total cost of VRB system and total cost of solar PV system. When the roof-top area is below $100m^2$, the annual electricity generation solar panel is only about 40kWh, but the total capital cost of CPCS is already above $300,000. When the roof-top area gets larger, the incremental electricity generated exceeds the incremental capital cost of CPCS, so the final break-even electricity price comes down due to economy of scale, as shown in Figure 17. Further, Figure 18 shows that when the roof-top area is small and the generation capacity is small, the total capital cost of VRB storage system is high than that of solar PV system; when the roof-top area goes above 2,000 m^2, the total cost of solar PV panels overtakes that of VRB system. This is mainly due to the decreasing capital cost per cycle with increasing energy capacity of VRB system discussed in Chen's thesis.

Therefore, a conclusion that can be made from Figure 16 is that car parks with large roof-top area available for installing more PV modules will be more economically attractive for building CPCS. In fact, IMM mall is one of the handful large shopping complexes in Singapore with large roof-top area. This is also another reason for choosing IMM for the initial stage of modelling.

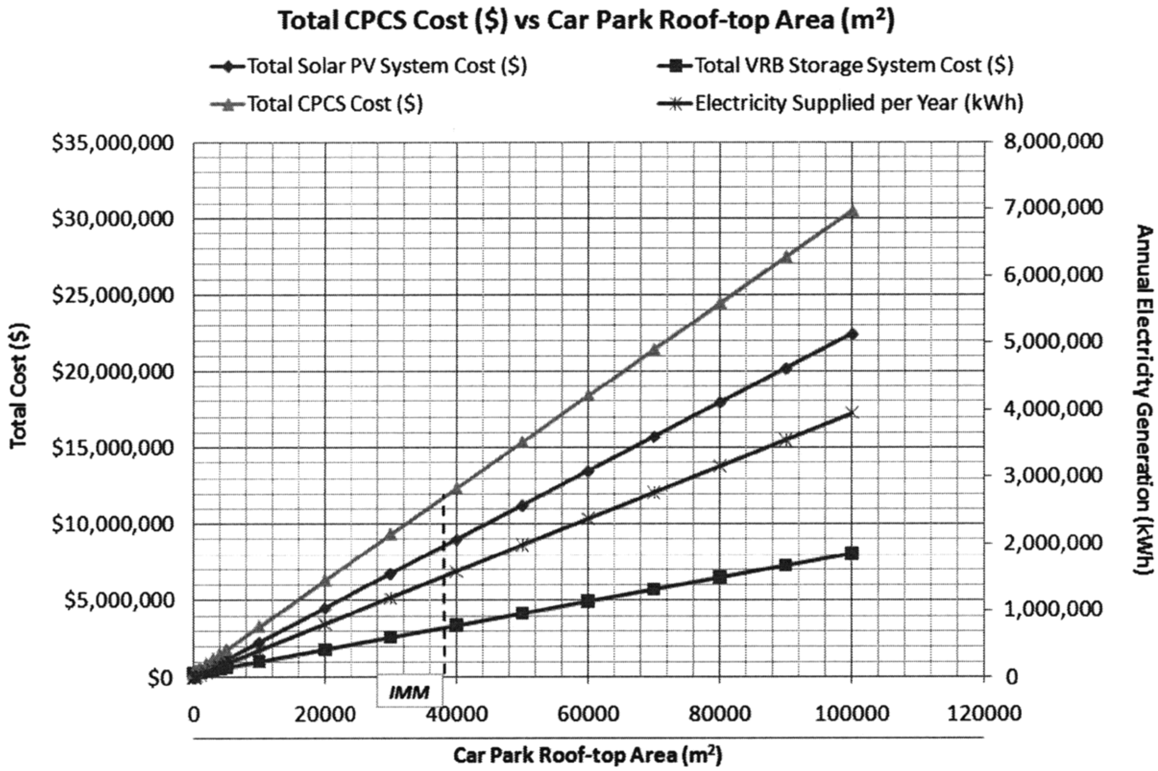


Figure 17: Total cost of CPCS, total VRB system cost, total solar PV system cost and annual electricity supplied by CPCS vs car park roof-top area (ranging from 1m^2 to 100,000m^2)

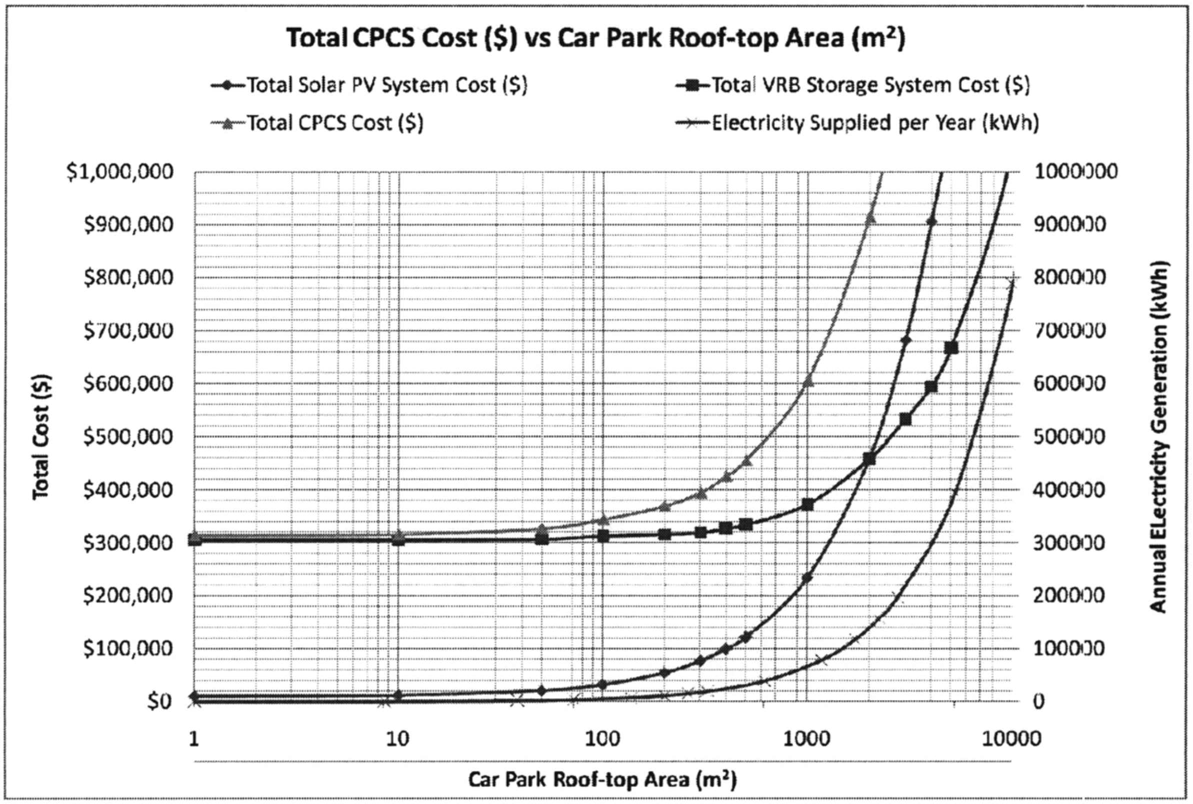


Figure 18: Total cost of CPCS, total VRB system cost, total solar PV system cost and annual electricity supplied by CPCS vs car park roof-top area (ranging from 1m^2 to 10,000m^2, log scale)

4.5.3 Carbon Dioxide (CO_2) Emission Reduction

Apparently, the price of electricity generated from the CPCS system modelled above is too expensive to be accepted by ordinary PHEV users, they may prefer to charge their vehicles from the household wall-plug with only one third of the cost of using CPCS.

However, the electricity generated from CPCS is totally carbon-emission free, and it is much "cleaner & greener" than the utility electricity generated from the ordinary power plants. Most of power plants in Singapore use natural gas to generate electricity, and power generation sector alone contribute the largest portion of total CO_2 emission in Singapore. This is shown in Figure 19 [2].

Key CO2 Contributors 2005 Kilo tones

	Electricity Generation	Industry	Transport	Buildings	Consumers/ Households	Others
Primary Consumption use combust fuel	19,315 (48%)	13,465 (33%)	7,056 (17%)	325 (1%)	216 (1%)	-
Secondary Consumption use electricity		8,328 (21%)	930 (2%)	5,910 (15%)	3,415 (8%)	732 (2%)
Overall		21,793 (54%)	7,986 (19%)	6,235 (16%)	3,631 (9%)	732 (2%)

TOTAL CO_2 = 40,377 kilo tonnes

Figure 19: CO_2 Emission by Sectors in Singapore in 2005.

In order to make the clean electricity generated from standalone solar electricity generation system with energy storage (SSEGS-ES) at least equally competitive with the gas-generated electricity, government's restriction on CO_2 emission is essential. This can be done in the form of carbon credit trading system seen in some European countries. In this system, carbon is being sought and bought just like other commodities in the market. The party who can reduce their CO2 emission will have more carbon credits to sell to those who need to emit more CO_2 than required by the government. In this way, PHEV users who use clean electricity to driven their vehicles will earn carbon credits, equivalently to reducing operating cost of PHEV. Therefore, in this implementation model of EV in Singapore, it is assumed that Singapore government has joined the global carbon trading system, and allows its citizen to participate in the trading activities just like trading stocks. A carbon trading price in \$/Ton needs to be determined in order to let solar-generated electricity and gas-generated electricity be equally attractive to EV users.

The carbon intensity from the two largest power generation companies in Singapore, Tuas Power [95] and Senoko Power [96] are used to estimate the mass of CO_2 emission when 1kWh electricity is generated from natural gas. Averaging the Senoko's carbon intensity in 2005 (450g/kWh) and Tuas' carbon intensity in 2006 (418g/kWh), the approximate carbon intensity for gas-generated electricity in Singapore is about *434g/kWh*. It is further assumed that the power transmission efficiency from power plant to end EV users is *98%*, so the actual carbon intensity per kWh electricity charged into EV is about *442.86g/kWh*.

Based on the previous modelling on IMM building, the price of electricity from CPCS is *\$0.2849/kWh*, and the utility (gas-generated) electricity price is *\$0.0932/kWh*, so the price difference is *\$0.1917/kWh*. In order to bridge this price gap, the CO2 emission per kWh of gas-generated electricity needs to be charged. The unit carbon price is therefore:

$$\frac{\$0.1917/kWh}{442.86g/kWh} \approx \$0.43287/kg = \$432.87/ton$$

Hence, in order to let solar-generate electricity's price and gas-generated electricity's price equal, the break-even price of CO2 should be *\$432.87/ton*.

4.5.4 "Best case" analysis

From the previous section, in order to let the solar-generated electricity be cost equivalent with the gas-generated electricity, a carbon trading price of \$432.87/ton would be needed. However, this price is about 20 times higher than the current carbon trading price in Europe (~\$21.30/ton [97]), and about 8 times higher than the predicted price in 2016 (~\$56.83/ton [98]). Therefore, it is very unlikely in the foreseeable future that Singapore's carbon trading price can be so high.

In order to estimate the lower limit of the break-even electricity price from CPCS installed in IMM building, a "best case" analysis is conducted. There are two major changes to the previous cost model.

(i) There will be a one million SGD (equivalent to $694,444.44 USD at 1USD=1.44SGD exchange rate) government financial support to offset partially the initial capital investment of the CPCS. This is based on the news release from the Economic Development Board (EDB) in 2008.

(ii) There will be no energy storage system implemented together with the solar PV panel systems. This is based on the assumption that the electricity generated at daytime can be 100% utilized or charging EVs instantaneously after it is generated. As a result, there will be no charging at night or during cloudy days, and there will no energy loss due to the storage system energy efficiency. The cost associated with the extra power conditioning system for smoothing the energy output from PV panels will be incorporated into the final DC/AC inverter cost. Therefore, the initial capital cost only includes the cost for solar PV system.

The final cost model parameters used to calculate a break-even electricity price are shown in Figure 20.

Calculating Break-even Electricity Price from CPCS ($/kWh)	
Total initial capital investment ($)	$7,793,381.39
Average interest rate	1%
Electricity output from VRB per day (kWh)	12,038.78
Number of CPCS's operating days per year	365
Total electricity supplied from CPCS per year (kWh)	4,394,154.56
Life cycle of CPCS (years)	20
Cost of electricity to EV users ($/kWh)	$0.1423
Annual revenue ($)	$625,361.09
Total bank loan ($)	-$7,793,381.39
Annual bank loan rate	5%
Loan payback period (years)	20
Equal annual installment for loan payment ($)	$625,361.09
Annual cash inflow ($)	$625,361.09
Annual cash inflow ($)	$625,361.09
Annual net cash flow ($)	$0.00
NPV of net cash flow in 20 years ($)	$0.00

Figure 20: Calculation of break-even solar-generated electricity price in the "best case"

The break-even price in the "best case" is therefore $0.1423/kWh (P1), about 1.5 times of the annual average electricity price in the past five years and about the same as the highest historical electricity price during the same five-year period. Based on the average electricity price (P2) of $0.0932/kWh, the price differential is $0.0491/kWh. The corresponding carbon trading price to let P1 and P2 equal is calculated as:

$$\frac{\$0.0491/kWh}{442.86g/kWh} \approx \$0.11087/kg = \$110.87/ton$$

This price is still about 5 times higher than current carbon trading price in Europe and about 2 times of the predicted price in 2016.

4.6 Summary

In conclusion, the final cost ($0.2849/kWh) those private EV users have to bear for using electricity generated from the SSEGS-ES system built in IMM building is too high to be accepted by the consumers. With the "best case" analysis in which there is government's financial support and no energy storage system is needed, the price of electricity from solar PV panels ($0.1423/kWh) can match the highest historical electricity price in the past five years in Singapore. Therefore, only with gas-generated electricity price above $0.1423/kWh, the solar-generated electricity will be more attractive to private EV users. Furthermore, this conclusion is drawn based on the assumption that the electric vehicles can only be charged at car parks when there is sunlight available. Sometimes, this might not be the most convenient to EV users.

5. Grid-tied PV-EV System (GPES) for Large Scale Solar Electricity Generation in Singapore

5.1 Background

To promote environmental friendly transportation in Singapore, the economics of transportation with Electrical Vehicles (EV) have been studied (refer to Fu's thesis), which includes the BEV model for taxi based public transportation and PHEV model for private vehicle transportation. As more than 97% of the electricity generation in Singapore are currently from non-renewable energy resources which mostly consists of natural gas and fuel oil[117], green electricity generation model based PV systems was analysed with the fact that solar energy is relatively abundant in tropical Singapore(refer to Sun's thesis). It has been shown that with government rebate of less than 35% of the total system cost, a PV system in its current stage of technical development with a capacity larger than 70kW can be a profitable investment, under the present government policy of equal electricity pricing.

In order to determine the economic feasibility and environmental benefits of feeding solar electricity to EVs, solar PV integrated EV charging system shall be modelled and evaluated.

The first model of the PV-EV system is built in a carpark as a standalone system where solar panels are installed on the roof of the carpark and charging spots are built around the parking lots. This model has been evaluated in previous sections as the Car Park Charging System (CPCS) model.

The second model of a PV-EV system is to build a large scale grid-connected PV system which feeds electricity to the grid at the electricity wholesale price. The EVs will get electricity directly from the grid. The objective of such a model is to determine whether it is economically feasible for an operator to install a large scale PV system whose electricity output could offset the electricity consumption of all private electrical vehicles (PHEV). The following analysis will be dedicated to this Grid-tied PV-EV System (GPES) model.

5.2 Methodology

In the GPES model, an aggregate roof area of state developed buildings is estimated, which will set an upper limit for the total area available to install PV panels as one integrated system by a single land use license. As electricity cost from larger systems is generally less than that from small systems due to price discount or minimal incremental cost, a system based on such an area will be calculated. The size of the area required to be able to charge all the EVs in Singapore will also be estimated and compared with this area upper limit to see how many EVs such a system can support. A feasible system based on practical restrictions will be determined and discussed in detail.

With such system estimations, the cost of electricity in terms of $/kWh will be calculated. This Grid-connected unit cost (Pg) will be compared with the utility Wholesale electricity price (Pw) and the conventional Combustion Engine vehicle (Pce). Similarly with the standalone CPCS model, the price comparison will enable us to determine the EV users' acceptance level as well as the economic feasibility of such a system with and without government incentives. Polices can also be suggested respectively to promote such a system.

5.3 Assumptions

The following assumptions are made in the detailed evaluation of the GPES model:

(1) The solar panel specifications used in this analysis is based on the CdTe thin film modules evaluated in Sun's thesis. The capital cost modelling of building such a solar PV system is also obtained from that thesis.

(2) The specifications of EV batteries and charging parameters are obtained from Fu's thesis on EV battery evaluation. Based on his thesis, it is assumed that Plug-in Hybrid Electric Vehicle (PHEV) is the most suitable model for private transportation-in Singapore. Herein, PHEV is used together with the GPES model as the model is based on private cars. The PHEVs are assumed to need to charge only once per day.

(3) The PV system is estimated to be able to operate for 20 years. An initial capital investment is assumed where changing of parts with lifetime shorter than this operation time will be discounted back to the Present Value (PV). Thus Net Present Values (NPV) of revenue and cost will be used for comparisons. The investment interest rate is set at 1% and the inflation rate is assumed to be zero in Singapore for discounting purposes. The lump-sum capital investment is taken from a bank loan with annual interest rate of 10%. The loan is paid back with equal annual instalment for the next twenty years. The annual instalment is likewise discounted back to the present value.

(5) The installation area will be leased by the government to the GPES operator for an annual royalty fee. The operator will install this solar PV system and sell electricity to the grid for revenues. The operator can be any individual or corporation or any other kind of investor.

5.4 Cost Model

5.4.1 Total Available Area Estimation

The largest portion of the state owned land area is used for residential and commercial developments. As the Housing Development Board (HDB) residential blocks are standard government built buildings which have roofs that are mostly non-shaded due to the multi-storey height, it is reasonable to take all the HDB roof areas as an aggregate unit to estimate the maximum allowable roof areas of the PV system.

According to the Housing Development Board, the total number of residential units under HDB's management is 885, 140 as of 31 March 2008[118]. Based on an average of 15 residential floors for each HDB block with 6 residential units on one floor, the total number of units per block is 90. Thus the number of blocks in total is around 9835. Then based on the assumption in Sun's thesis that there is one multi-storey carpark every 4 HDB blocks of residence and such a unit has an estimated area of $3870m^2$. Taking into consideration of the carpark shading and the non carpark integrated old buildings, we can take half of the car park area, which gives an average area of $3225m^2$ for the 4HDB-Carpark unit. Thus with 9835 blocks, the total number of such unit is around 2459. The total available area is thus estimated to be around $7.93km^2$. The detailed estimations are shown in Table 17 and Table 18.

	No. of 4-room flat	No. of 5-room flat
	4	2
Standard Area(m2)	85	110
Floor Area(m2)	340	220
Flat Floor Area(m2)	560	
Excess Area(m2)	85	
1 HDB Roof Area(m2)	645	
Total HDB Roof Area(m2)	2580	
Car Park Roof Area (m2)	645	
Total Roof Area of a 4HDB-Carpark Unit (m2)	3225	

Table 17: Average Area Estimation for an HDB-Carpark Unit

	Till 31-Mar-08
HDB Dewling Unit in 2008	885,140
Residential Floors per HDB block	15
units per floor	6
Number of Units per Block	90
Number of Blocks	9835
Number of HDB-carpark Unit	2459
Total area (m2)	7929379.17
Total Area (km2)	7.93

Table 18: Total Available Area Estimation for the GPES Model

5.4.2 Area Requirement for the PV System to Charge All Private PHEVs

The PHEVs are driven by advanced Li-ion batteries which can be plugged into any normal power socket that provided 240V AC power supply. The characteristics of the model of Li-ion batteries are elaborated in Fu's thesis and reference [116], as shown in Table 19. To be consistent with the previous models, the charging efficiency is assumed to be 90%.

By the end of 2007, total number of private cars in Singapore is 451,745[119]. If all these cars are replaced by PHEVs or a 100% market penetration, then the total charging energy requirement for one day will be 8.8kWh*451,745/90%, which is 4417.06 MWhs. As the solar panels are at a 10% efficiency with an 20% percent system loss for a grid-tied PV system, the energy production per day from $1m^2$ solar panel is 1000W/m2*10%*80%*4 peak hours, which is 0.32kWh. Thus the area needed to output 4417.06 MWhs of energy per day with a 90% panel overhead is 4417.06 MWhs/0.32/90%, which is around $15.41km^2$. The details are shown in Table 19. As this area is more than twice the total available area of $7.93km^2$, the GPES system based on HDB residential unit is only able to supply around ***51.4%*** of market penetration.

Battery Capacity (kWh)	15
Depth of Charge/Discharge (kWh)	8.8
Charging Voltage (AC Volts)	240
Charging Current (Amp)	7.5
Charging Power (kW)	1.8
Charging Time (hrs)	4.89
Solar Irradiance(W/m2)	1000
Daily Peak Hours (hrs)	4
Solar Module Efficiency	10%
System Efficiency	80%
Total energy per day per m2 of panel (kWh/m2)	0.32
Number of **private cars**	451,745
Market penetration	100.00%
Total no. of PHEVs	451745
PHEV Charging efficiency	90%
Total energy required (kWh) per day	4417062.22
Panel area needed (m2)	13872595.72
Percentage overhead	90%
Total area needed (m2)	15413995.24
Total area needed (km2)	15.41

Table 19: Total Required Area Estimation to All Private Cars (PHEV)

5.4.3 Electricity Cost Estimation

Based on an available roof area of 7.93km^2, with the same grid-connected model that was discussed in Sun's thesis for the HDB-Carpark residential model, the total production capacity is as high as 568MW. The cost of such a system is more than 2.86 billion US dollars or 4.12 billion Singapore dollars. The electricity cost is estimated as US$0.172/Wp or S$0.248/Wp.

5.4.4 Analysis for a Practical System of 50MW Capacity

Though Singapore has such a potential to achieve more than 568MW capacity, however there is a limit for the amount of power to inject into the grid in order to avoid grid stability and reliability issues. In Singapore, the regulations on grid transmission are set by Energy Market

Authority (EMA), which is acting as the Power System Operator (PSO) of Singapore. In the latest version of the Electricity Market Rules published on 1 July 2009, there hasn't been specific documentation of non regulated electricity such solar electricity or wind[120]. Thus here the electricity feeding limit to the grid is set as 50MW which is the amount currently required for general grid reliability[120] with a peak grid transmission level of around 6GW and a generation capacity of around 9.775MW [99].

*a. **Electricity Cost Estimation***

Based on the grid-connected PV system analysed before, the area needed for 50MW capacity is around 697900 m^2. As the area is around 100 times larger than the area increase compared with the grid-tied HDB-carpark model from Sun's thesis, all the cost components will be changed accordingly based on such a size.

For such as system, the electricity cost didn't change much as compared with the previous case, which stays at $0.172/kWh as the 568MW case, shown in Table 20. The total capital cost is now around 200.3 million US dollars. With 100% loan financing, the cost is increased by more than two times to around 424.5 million US dollars and the electricity cost is increased to $0.365/kWh. Among the cost of various components, the module cost is the largest part which accounts for around 50% of the total capital cost, as shown in Figure 21, which is the general case for grid-connected systems.

Cost Calculation		Percentage Cost
Module Cost ($)	100000000.80	50%
DC/AC Inverter Cost ($)	29288199.24	15%
Installation Cost ($)	25425575.86	13%
NPV of Maintenance and Licensing Cost ($)	45576431.99	23%
		100.00%
	USD-SGD	1.44
Total Cost (USD-SGD)	200,290,207.89	288417899.37
Annuity for 20 Years	23526012.66	33877458.24
Net Present Value of Total Cost with Loan Financing	424,539,907.63	611337466.98
Installed Cost Per Watt (/Wp)	8.49	12.23
Electricity Cost with Loan Financing (/kWh)	0.365	0.526
Electricity Cost Without Loan Financing (/kWh)	0.172	0.248

Table 20: Cost Estimation for a 50MW Generation Capacity

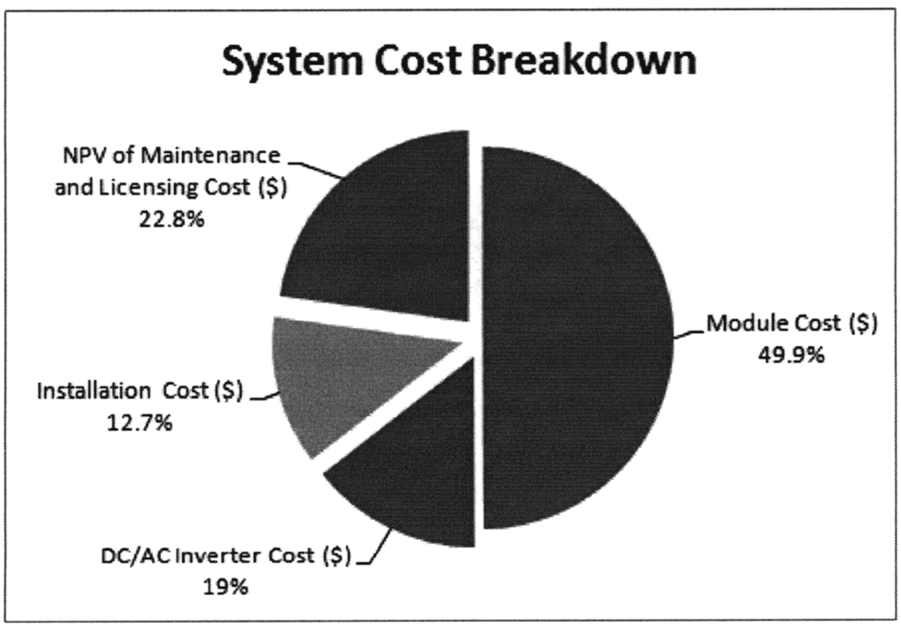


Figure 21: Relative Percentage Cost of GPES with 50MW Capacity

b. Revenue and Profit Estimation

The average electricity wholesale price is at US$0.109/kWh or S$ 0.157/kWh quoted from Sun's thesis and it will be used for revenue estimation. As the yearly energy production is around 58,108,365.5 kWhs, the yearly revenue will be around 6.33 million US dollars (58,108,365.5kWhs x $ 0.109/kWh). With the previous cost estimations, the profitability is estimated. And there is a net loss even without financing the capital investment and the loss is larger with loan financing. The details are shown in Table 21.

	USD-SGD Exchange Rate	1.44
	USD	SGD
Total Cost	424,539,907.63	611,337,466.98
Revenue	126,676,236.71	182,413,780.87
Profit with Loan Financing (/kWh)	-297,863,670.91	-428,923,686.12
Profit without Loan Financing (/kWh)	-73,613,971.18	-106,004,118.50

Table 21: Revenue and Profit Estimation

5.5 Economic Feasibility Analysis and Environmental Benefits

5.5.1 Electricity Price Sensitivity with System Size

All the above analysis has been based on the 50MW capacity. The capacity dependence of electricity price is the same as that plotted in Figure 1. As the size increases, the electricity cost will stabilize when the capacity exceeds 30-40MW capacity, eventually to a price of $0.172/kWh without loan financing and $0.365/kWh with 100% loan financing at a rate of 10%.

5.5.2 Investment Evaluation for the Solar Operators with Government Rebate

As this system is not profitable, it is not considered as a good investment without government incentives. The government rebate policy for solar PV system is stated by EDB in the solar capability scheme, which gives a rebate of 30 to 40% of the total capital investment, but capped at 1 million Singapore dollars[94]. With a capital cost that is over 200 million USD, which is more than 288 million Singapore dollars, the maximum 1 million SGD government rebate is only able to add 1 million SGD to the current negative 106 million SGD profit. Thus the current rebate available from the government is insignificant and will not make the system breakeven, as shown in Table 22.

In the case with external capital cost financing, the net loss is higher, making the government rebate option further out of the question, as tabulated in Table 23.

5.5.3 Investment Evaluation with Electricity Price Commission

An alternative government incentive is to set a Feed-in Price Tariff for solar electricity fed into the grid. The breakeven price will be equal to the electricity cost. Thus the breakeven price shall be \$0.172/kWh without loan financing of capital cost, while it is \$0.365/kWh with loan financing. For the investment to be economically preferable than its next best alternative, which is assumed to be 1% annual return from the capital cost, the price in the case without loan financing is \$0.204/kWh. In the case with loan financing, the opportunity cost case will not exist since the capital is not available at hand and has to be financed. The details are listed in Table 22 and Table 23.

5.5.4 Carbon Dioxide (CO2) Emission Reduction

From the above analysis, it is apparent that the electricity generated from a large scale grid-tied PV system in Singapore is still too expensive without any government incentives. And it will be not able to compete with current grid electricity price which is at almost half of the PV electricity cost. PV electricity thus will not be attractive to PHEV users at the PV system's current stage of technical development.

However, the main advantage of solar electricity lies in its clean and renewable resource. And it is environmental friendly with zero emission as compared to the current grid electricity which is mostly generated from non-renewable fossil fuel resources such as nature gas and oil, as described in Part one of the project and in the previous CPCS model.

With global environmental concerns as one of the most important issues in the world, every government has the responsibility to reduce green gas emission, among which CO2 is a key component. To ensure global environmental sustainability in the long term, restriction on CO_2 emission shall also be put forward by the Singapore government. As mentioned in the previous models, this can be done in the form of carbon credit trading system seen in some

European countries. Similarly with before, the environmental benefits of grid-tied PV electricity shall be analysed based on the carbon trading system mentioned previously.

As the carbon intensity of the current grid electricity is 434g/kWh, and the cost of electricity from the 50MW GPES without loan financing is US*$0.172/kWh*, and the utility (gas-generated) average wholesale electricity price is US*$0.1090/kWh*, so the difference is US*$0.063/kWh*. Similarly, to bridge this price gap, the CO2 emission per kWh of gas-generated electricity needs to be charged. The unit carbon price is therefore:

$$\frac{\$0.063/kWh}{434.0g/kWh} \approx \$145.16/ton$$

Hence, in order to let the large scale grid-tied electricity's price competitive with the gas-generated utility electricity's price, the break-even price of CO2 should be *$145.16/ton*.

When 100% loan financing is applied, the cost of electricity is *$0.365/kWh*, and in this case, the unit carbon price to bridge the gap between this cost and the current utility wholesale electricity price of US*$0.1090/kWh*, the unit carbon price is thus

$$\frac{\$0.365/kWh - \$0.109/kWh}{434.0g/kWh} \approx \$590.78/ton$$

However the current carbon trading price in Europe is ~$21.30/ton [97], which can compensate a cost of $0.0092/kWh, as calculated as follows:

$$\$21.30/ton * 434.0g/kWh \approx \$0.0092/kWh$$

Even with the predicted price in 2016 (~$56.83/ton [98]), there still exist a gap between the carbon trading price and the requirement. The details are listed in Table 22 and Table 23.

5.5.4 Capital Cost Reduction with Hardware Price Drop

If considering the cost reduction of hardware, especially the two most important component, the module and the inverter. The cost has to be reduced by 36.6%[2]. With 50% of the capital cost taken by modules, the module price has to reduce by 74.0% from \$2.00/Wp to \$0.54/Wp in order to make the system breakeven. If considering the cost compensation from CO2 trading at the current trading price, the module price is only required to drop by 62.8% to \$0.74/Wp.

In the case with loan financing, which results in a higher cost, the reduction of capital cost has to be 71.9% without consideration of CO2 trading and 69.4% with consideration of CO2 trading. As the modules and inverters together account for only 69% of the capital cost, even when both the module price and inverter price drop to 0, the system cannot breakeven.

The details are listed in Table 22 and Table 23.

Total Cost: \$200,290,207.78;	**Installed Cost Per Watt: \$4.01/Wp**		
Rebate	MAX 40% to 1M SGD → **cannot breakeven**		
Feed-in price to breakeven	\$0.1724/kWh	**\$0.163/kWh w/ CO2**	**S\$0.235/kWh w/CO2**
Feed-in price to be economically preferable	\$0.204/kWh	**\$0.195/kWh w/CO2**	**S\$0.280/kWh w/CO2**
CO2 trading price required to breakeven	**(\$0.172- \$0.109)/kWh / 434g/kWh= \$145.16/ton**		
Cost Reduction Requirement to breakeven: **(0.172 or 0.163 -0.109)/0.172=36.6% or 31.4%**	**Module price: Drop by 36.6%/50% = 74.0% to \$0.54/Wp** **: Drop by 31.4%/50% = 62.8% to \$0.74/Wp** w/CO2		

Table 22: Profitability Sensitivity Analysis without Loan Financing

[2] (\$0.172/kWh-\$0.109/kWh)/\$0.172/kWh= 36.6%

Total Cost: $424,539,907.63;	**Installed Cost Per Watt: $8.49/Wp**		
Rebate	MAX 40% to 1M SGD → cannot breakeven		
Feed-in price to breakeven	$0.365/kWh	$0.356/kWh w/CO2	S$0.513/kWh w/CO2
CO2 trading price required to breakeven	($0.365- $0.109)/kWh / 434g/kWh= $590.78/ton		
Cost Reduction Requirement to breakeven: (0.365 or 0.356 -0.109)/0.356= 71.9% or 69.4%	Module and Inverter Cost (69%) drop to 0 → cannot breakeven		

Table 23: Profitability Sensitivity Analysis with Loan Financing

5.6 Summary

To summarize, in the 50MW Grid-tied PV-EV Electricity System (GPES) just analyzed, the cost of $0.172/kWh is still too high for solar electricity to compete with the current gas generated utility electricity at a whole sale price of $0.109/kWh without any government incentives. With a system cost of 288 million Singapore dollars with loan financing, the maximum government rebate of 1 million Singapore dollars is insignificant due to the huge size of the base. The alternative of Feed-in Price Tariff can be used to offset the electricity cost with a price around 1.6 times or 3.5 times higher than the current electricity price under the case without loan financing and with loan financing respectively.

Without government incentives, the electricity cost can be offset by a small amount through carbon trading with its reduction of CO2 emission. It was found that 7 times increase from the current carbon trading price of ~$21.30/ton is required to offset the difference between PV electricity cost and the current utility electricity wholesale price in the case without loan financing.

Thus currently, to make PV system feasible as an investment option, Feed-in Electricity Price Tariff can be set to buy the solar electricity fed into the grid.

In the future, as the PV system capital cost keeps decreasing with the hardware technological advancement, as well as the fossil fuel generated utility electricity price and CO2 trading price are likely to rise due to depletion of fossil fuels and growing global environmental concern.

When the PV electricity cost is comparable with utility electricity price, Electrical Vehicles can then run partly on green electricity to promote a green transportation system in Singapore.

6. Concluding Remarks on the Implementation Models

Based on the four implementation models, a few concluding remarks can be drawn about the prospects of the green technologies evaluated in this group Project.

6.1 Environmental Benefits

The main cause of implementing XEVs lies in its environmental benefits.

As shown in the Swapping Station Model, a BEV taxi can reduce 25-31 tons of CO_2 emission every year. A penetration of 5% in the taxi market (a total of 1250 BEV taxis) would mean at least 31 kilo tones of CO_2 reduction. This reduction can be further increased to more than 38 kilo tones, nearly 0.1% of the total CO_2 emission in Singapore, if renewable energy is used to power up BEVs. Of course, at higher BEV taxi penetration rate, the environmental gains will increase further. From the Private Car model, a PHEV user who drives 40 miles a day is able to achieve 3.0806 tons of CO_2 reduction per year. Since private car sector is the largest in the automobile market in Singapore, replacing gasoline cars with PHEV for private car users is a key to the CO_2 reduction in transportation sector.

XEVs are still at its early stage of development. It is expected that these "green" cars' fuel efficiency will be continuously improved along with the booming green vehicle industry. At the mean time, the rapid development of PV technologies could also lead to PV panels of higher efficiencies at lower cost. As a result, these environmental gains of XEVs and the XEV plus renewable energy system can be further enlarged in the near future.

6.2 Political Benefits

Politically, with a XEV system in place, Singapore can demonstrate to the world its determination to reduce the absolute carbon emission in order to meet the Kyoto Protocol requirement.

Singapore has a high CO_2 emission per capita, reflected by its high energy consumption. Figure 22 shows the energy consumption per capita for a few selected countries including Singapore. This graph is plotted based on statistics from Energy Information Administration (EIA)'s International Energy Statistics and International Energy Agency (IEA)'s Key World Energy Statistics 2008 [121]. The large difference between these two sets of data for Singapore is mainly because that the former takes into account of energy consumed by marine bunkers at the Singapore port. Nevertheless, both data suggests that as an oil refining center, this small island country has a high energy consumption rate per capita, which is at the same level as other developed countries.

Singapore is one of the Annex-B countries in the Kyoto Protocol. Therefore, Singapore does not hold any imperative obligation in reducing its absolute GHG emission as compared to countries in Annex-A list in the first phase before 2012. However, the high GHG emission has brought many pressures to Singapore. BEV system, on the other hand, will help improve the image of this highly industrialized city state, and demonstrate the government's resolution toward environment protections.

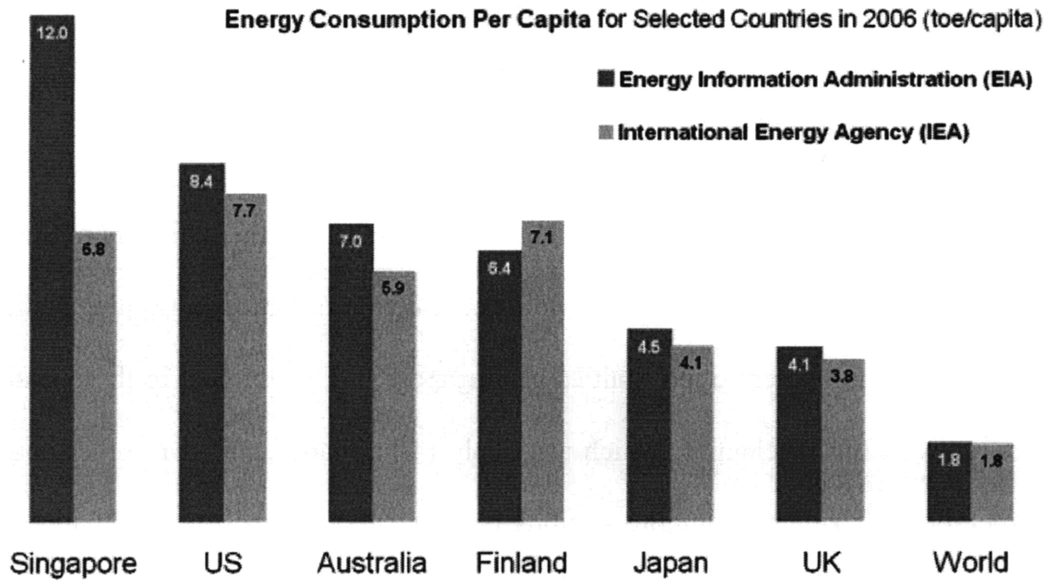


Figure 22: CO2 Consumption Per Capita for Selected Countries in 2006 [121]

6.3 Social Benefits

Socially, implementing XEV system helps to raise the awareness of environmental conservation and it also helps Singapore to maintain its status being a green and clean city in the world.

The low noise level of XEV compared to conventional cars can greatly enhance people's driving experience, reduce noise pollution in city areas and project an environmental-friendly image of Singapore to the world.

6.4 Economical Barriers

Implementing XEVs requires a large amount of upfront capital cost as compared to gasoline cars. Government incentives are necessary to help introduce XEVs into the Singapore market. However, the largest barrier also lies in this high capital cost.

While the government incentives are essential for implementing XEVs, however, the Singapore Government does not reap many economic benefits from this system. Firstly, the major cost of XEV systems is from battery. Battery suppliers are mainly from Japan, Korea, and U.S. In Singapore, there is rarely any industry directly related to battery manufacturing. Secondly, one important consideration to promote XEV in U.S. is to save its automobile industry. Unfortunately, Singapore does not have its own automobile industry either. All cars in Singapore are imported from other countries. Moreover, while construction of battery swapping station can possibly create some employment opportunities in Singapore, the major cost in these stations is from the battery swapping mechanics, which are likely to be manufactured in other countries. Lastly, the operation of battery swapping stations is developed towards an automatic system. This is to minimize staffing cost and make the process more convenient for XEV drivers. However, such operation requires very little manpower, thus does not create many employment opportunities in Singapore.

In the development of solar industry in Singapore, so far there is no policy in place to specify a certain percentage of electricity which must be from the renewable energy by a certain time; there is no sign showing that the government will provide feed-in-tariff for solar electricity as well. Instead, the government emphasizes that "energy cost should be borne in full by end-users", because the government believes that subsidization would "dampen price signals and create the incentives to over-consume" [7]. However, the solar electricity is still too expensive to be accepted by most users at its present price level. The estimated present price level of S$0.175/kWh is based on the cost effective large grid-tied PV system at its state of the art technology.

It appears that the Singapore Government put more focus on growing the industry to create more employment opportunities and generating revenue, rather than emphasizing the PV application in Singapore. Therefore, a large scale of deployment of PV probably will not happen in a short term. It is more likely that the government will wait for the cost of this technology to go down.

6.5 Summary

In a nutshell, despite of environmental, political and social benefits, currently the high cost of XEVs system prevents it from entering the Singapore market easily, as the government support is not strong enough. Under current policies, battery swapping model and private car model are not cost-effective compared with their gasoline counterparts. However, this situation would change if gasoline price goes up, or if the government taxes the CO_2 emission.

\$70.21/ton CO_2 price is necessary to make the cost of BEV taxi system competitive to that of gasoline taxi system. With increasing CO_2 trading price, it is highly possible to see BEV taxis running on the road in next ten years. On the other hand, \$378.3445/ton CO_2 price is needed for PHEV to breakeven. This is 17.5 times of the current CO_2 trading price in the EU. As the private cars contribute the most CO_2 emission in the transpiration sector and PHEV fits the needs of private users well, further rebate must be given for PHEV to be accepted by Singaporeans.

Solar energy could provide "clean" electricity for the XEV system and maximize its environmental benefits. Currently only a few trial sites are built to study the feasibility of roof-top PV in Singapore, and a long time into the future is required for PV electricity to be competitive with utility electricity.

With energy storage system, the electricity generated from solar energy can have better quality and longer available usage time (not only during sunny daytime.) However, the cost of solar energy and storage system at present level is still too high to be generally accepted in Singapore. Again, it is expected that with increasing oil price volatility and reduced technology costs, solar energy with storage system can start to have its market niche in the future.

In the best scenario, XEV, solar PV and storage technology will become mature during the same period. A combination of them would generate the maximum benefits. For example, a total of only 1250 BEV taxis running on solar electricity could save about 38 kilo tons of CO_2 per year.

However, if the oil price rises rapidly within a short period, it is possible to have a XEV system relying on fossil fuel generated electricity. In this scenario, these 1250 BEV taxis can still reduce CO_2 emission by 31 kilo tons every year, compared to gasoline cars. Before that, the best way in reducing CO_2 emission from the transportation sector is probably promoting public transport.

7. Conclusion

In this project, we briefly reviewed the car, energy and solar energy (electricity) market in Singapore. Firstly, while the car population in Singapore is strictly under control by the government through various policies, the car demand remains strong in Singapore. Seeing the positive environmental impacts of green vehicles, the Singapore government also introduced "green vehicle rebate" to encourage the growth of green vehicles in Singapore. Although the total quantity of green vehicles remains small, the growth rate in recent years has been quite significant. For example, the number of hybrid cars was almost doubled from 1057 in Year 2007 to 1999 in Year 2008. Secondly, it is noticed that Singapore relies heavily on natural gas imported from neighboring countries for its electricity generation, which consists of nearly 76% of its electricity fuel mix. Singapore has an urgent need to diversify its electricity mix. On the other hand, its total installed electricity generation capacity of about 10 GW is almost twice of its peak demand. This excess power generation capacity can potentially provide electricity for the XEV system. Lastly, the government is also heavily investing in solar industry. While most of photovoltaic panels made in Singapore are for export, the government is investigating the application of building integrated photovoltaic (BIPV). This renewable solar energy can be another source of electricity generation. It can also provide "green" electricity to the XEV systems to make these vehicles truly "green".

To further understand the economics and feasibility for generating renewable energy, both photovoltaic and solar thermal technologies are investigated.

For photovoltaic systems, it is found that at the current stage of technological development, the cost of modules and inverters take the largest part of the total system cost. Among all types of solar cell and module technologies, crystalline Si based PV technology has the best performance in terms of efficiency and system reliability, while thin film technologies have the lowest cost. Among all types of in market thin-film technologies, the CdTe thin film modules from the First Solar has the best efficiency to cost ratio, even when operating in land-scarce Singapore where cell temperature can reach as high as 60°C. Thus CdTe module from First Solar has been used for the PV system analysis. With the rest of the components assumed to be at their latest state of technical development, it is found that for a large scale PV system deployed at HDB roof tops, the solar electricity cost is around \$0.172/kWh, which is not market competitive as compared with the average utility wholesale electricity price (during sunny daytime) of \$0.109 dollars. If carbon trading is considered, PV systems' zero emission advantage would enable it to gain additional profit to offset its cost. It is found that the current carbon trading price of \$21.30/ton is able to offset the difference between solar electricity cost and utility electricity price by \$0.0092/kWh. With the current trend of price increase for carbon trading, we foresee the competiveness of large-scale grid-tied solar electricity in the near future.

It is also found that concentrating solar thermal technologies is not suitable for Singapore. Firstly, in a concentrating solar power (CSP) system, only direct normal insolation could be focused to solar receiver and transformed into thermal energy. This thermal energy is used to generate steams and drive a conventional turbine motor to produce electricity. However, in Singapore about 40% of its daily radiation belongs to diffuse radiation; only an average of 2.4 kW/m^2 direct normal insolation (DNI) is available daily. On the other hand, to make CSP systems economic, usually a daily DNI of 6 $kW/m^2$is required. Secondly, CSP plants occupy a large area to collect solar radiation. Even though parabolic trough power plants require the minimum land areas among all CSP plants, Nevada Solar One – a newly built 64 MW parabolic trough plant – takes up a vast area of 1.6 km^2. It is impractical for Singapore to have such a large area just for building a power plant because of its limited land. These two factors make the concentrating solar power technology unsuitable for the Singapore market. Instead, BIPV may be a good option for Singapore to acquire solar energy. Nevertheless, CSP plants, especially the parabolic trough power plants, still have a huge market in sub-desert or desert areas with rich DNI, such as south-western US and Mediterranean countries. In recent years, significant progress has been made in the research field related to parabolic trough technologies, such as receivers with better optical efficiency, solar mirrors of lower cost, and heat transfer fluid operating at higher temperature. All these efforts have been continuously bringing down the cost of solar electricity. Parabolic trough power plants will play an important role in the large scale central power generation in its niche market.

Since battery will be the most critical part for electrical vehicles, lithium ion battery technologies are examined in order to choose one specific battery technology to meet the technical specifications. It is found that both manganese and phosphate based lithium ion batteries are potentially suitable for XEVs. With higher durability and lower cost, $LiFePO_4$ battery is expected to have higher utility for XEVs.

Large-scale energy storage system using flow battery technology, more specifically the vanadium redox flow batteries (VRB), is also evaluated together with other technologies mentioned above for integrated implementation models. Flow battery is known for its decoupled energy/power management, and its scalability for various application requirements. Though its energy density and power density may not be as high as its competitors, such as NaS and Li-ion systems, its relatively low unit cost, extended lifecycle and convenient O&M make it one of the few fast growing electro-chemical storage technologies in the market.VRB is one of the most promising candidate in the flow battery family meeting the future demand, mainly because of its environmental friendliness and decreasing unit capital cost. However, based on the models presented in the project, implementing flow batteries system for large-scale energy storage in Singapore is still not very financially viable at present. The main obstacle is the cheap energy (electricity) cost in Singapore. On the other hand, with expected increasing gas price volatility and more government support for environmental conservation (such as carbon credit trading), also with the improved flow battery performance and decreased unit capital cost, large-scale energy storage will become the soon-to-be "sun-rise" market in Singapore.

Based on these findings, four different models are built and evaluated. In the first model, battery electric vehicle is identified as a suitable candidate to replace the gasoline taxi because it offers reduced CO_2 emission, and lowered noise level especially in a long driving distance. This BEV taxi system will implemented together with battery swapping stations as supporting infrastructure. From the economic analysis, we found that based on the average electricity and gasoline price from 2005 to 2009 ($0.093/kWh for electricity and $1.86/gallon for gasoline), the cost per mile for BEV and gasoline car is $0.217 and $0.199, respectively. To bridge this price gap, a carbon tax of $70.21/ton is required to be placed on gasoline taxis. On the other hand, when the gasoline prices rises above $2.4/gallon, BEV taxi will become more competitive than gasoline taxi in terms of cost per mile. Furthermore, each BEV taxi can help to reduce about 25 tons of CO2 emission every year. This reduction can go up to 35 tons if the electricity is from renewable source instead of natural gas fired power plant. Therefore, if all the gasoline taxis are replaced by BEV taxis, total 855.61 kilo tons of CO_2 reduction can be achieved. This will be about 2% of the total CO_2 emission in Singapore (40, 377 kilo tons in 2005).

In the second model, PHEV is found to be suitable for private user for its acceptable price, less CO_2 emission and lower operation cost. By using the same gasoline and electricity prices as in the first model, the cost of PHEV is still higher than gasoline car under current Green Vehicle Rebate scheme. In order for PHEV to breakeven, a CO_2 trading price of $378.34/ton is needed and this is 17.5 times of the current CO_2 trading price ($21.6/ton) in the EU. Hence, PHEV is unlikely to be adopted at present as private transportation unless more incentives are given by the government.

In the third model of car park charging system (CPCS), a stand-alone solar (PV) electricity generation system with energy storage is built for a car park charging system (CPCS) in a large shopping complex in the south-western Singapore. The objective of such CPCS is to help increase the electric vehicle penetration and make those EVs "greener" in Singapore. Based on a cost model of making full use of the available roof-top area for solar PV panels (>34,000m^2) and charging electric vehicle at maximum electricity storage capacity (2.5MW, 10MWh), the final electricity cost from the CPCS is about $0.285/kWh. This is about three times of the average gas-generated electricity price in Singapore from 2005 to 2009 ($0.093/kWh). In order to make the CPCS-generated electricity financially equivalent to gas-generated electricity, carbon credit should be awarded and the calculated break-even CO_2 price is about $432/kWh. This figure is about 20 times of the current carbon trading price in the EU and 8 times of the predicted price in 2016. A "best case" is also carried out in which the energy storage system is excluded and government's financial aid is considered. The final result show that only with gas-generated electricity price goes above $0.1432/kWh, could the CPCS becomes economically feasible. However, the trade-off in the "best case" would be the less availability of electricity when there is no sun-light available.

In the last model of a large-scale grid-tied PV-EV electricity System, the economic feasibility of building a 50MW large scale grid-connect PV system with the state of the art technology on the top of HDB roofs was considered. The total area required for such a system is 697,900m^2 and the cost is around 255 million Singapore dollars. The cost of electricity without any government incentives is around US$0.172/kWh, higher than utility electricity wholesale price at US $0.109/kWh or S$0.157/kWh. If considering the maximum government rebate of 1 million Singapore dollars, the change to the electricity cost per kWh is insignificant due to the huge size of the base cost. However, if an electricity price commission is given to solar electricity either by the government offset or by a forced higher buying price from the utility, the price of the electricity only needs to be increased to US\$0.172/kWh to make such a PV system profitable. To make the system economically viable, it was found that an electricity price of US\$0.204/kWh is required. If carbon trading is also considered at the current trading price, a cost compensation of \$0.0092/kWh can be derived. Based on the trend of CO2 trading price increase and the trend of PV system hardware cost reduction with technology improvement, feasibility of PV systems in Singapore is foreseeable in the near future.

From the economic analysis on different XEV models, it is found that at current stage, strong government incentives are necessary to implement XEV system. However, the government seems quite lukewarm about the XEVs. This is most likely because that there is no car and battery industry in Singapore. Heavy investment in XEV system does not necessarily stimulate the economy much. In addition, as an Annex-B country in Kyoto Protocol, the pressure on CO_2 reduction is not desperately urgent for Singapore; and the relatively small reduction of CO_2 by implementing XEVs systems does not provide enough driving force for the country to adopt green vehicles on a large scale. After all, promoting public transportation offers another economical alternative for the government. From the Tie-to-Grid model, it is also found that solar PV electricity is still not cost competitive with the current utility price at its present stage of technical development.

While a few trial sites have been built to test the feasibility of roof-top PV in Singapore, it is believed that Singapore is still waiting for PV price dropping down before a large scale deployment. Air-conditioning seems a good usage for this renewable energy, before the XEV systems are implemented.

References

1. Valentine, S. *PROFITING FROM A TRANSITION TO RENEWABLE ENERGY: LESSONS FROM SINGAPORE.* 2008; Available from: www.spp.nus.edu.sg/wp/wp0703.pdf
2. MEWR. *National Climate Change Strategy.* 2008 [cited 2009 Jan 16]; Available from: http://app.mewr.gov.sg/web/Contents/ContentsNCC.aspx?ContId=452.
3. U.S. Department of Energy. *Fuel Economy: Electric Vehicles.* [cited 2009 Jan 19th]; Available from: http://www.fueleconomy.gov/Feg/evtech.shtml.
4. Deutsche Bank, *Electric Cars Plugged In.* 2008.
5. ISWARAN, S. *Speech of the Singapore Minister at the launch of Solar Energy Research Institute at NUS.* 2008 [cited 2009 Jan 8]; Available from: http://www.egovmonitor.com/node/17334/print.
6. EDB Singapore. *Clearn Energy.* [cited 2009 Jan 9]; Available from: http://jingfaju.com/edb/sg/en_uk/index/industry_sectors/clean_energy.html.
7. Hussain, Z. *Why no subsidies for solar power.* 2008 [cited 2009 Jan 8]; Available from: http://wildsingaporenews.blogspot.com/2008/03/singapore-gives-solar-energy-sector-20m.html.
8. Wikipedia. *Singapore.* [cited 2009 Jan 7]; Available from: http://en.wikipedia.org/wiki/Singapore.
9. Jiang, F. *Investigation of solar energy for photovoltaic application in Singapore.* in *Power Engineering Conference, 2007. IPEC 2007. International.* 2007.
10. T. Markvart, *Chapter 2.2 Energy from the Sun*, in *Solar Electricity.* 2000, John Wileys & Sons, Inc.: Southampton, UK.
11. F. Antony; C. Durschner and K-H Remmers, *2.5 Estimating the Output of PV Systems, Array Angles and Orientation*, in *Photovoltaics for Professionals: Solar Electric Systems Marketing, Design and Installation.* 2007, Solarpraxis AG: Berlin. p. 72.
12. EIA, *International Energy Outlook 2008 by Energy Information Administration.* 2008, U.S. Department of Energy: Washington, DC.
13. H.-H. Rogner, D.Z., R. Bradley. P. Crabbé, O. Edenhofer, B.Hare (Australia), L. Kuijpers, M. Yamaguchi,, *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, in *Climate Change 2007: Mitigation.*, O.R.D. B. Metz, P.R. Bosch, R. Dave, L.A. Meyer, Editor. 2007: New York, NY, USA.
14. European Photovoltaic Industry Association, *Global PV Market Outlook Until 2013.* 2008: Brussels, Belgium.
15. Earth Policy Institute, *Solar Indicator Data*, E.P. Institute, Editor. 2007: Washington D. C., USA.
16. Wikipedia. *Sunlight: Calculation.* 2009; Available from: http://en.wikipedia.org/wiki/Sunlight#cite_ref-0.
17. University of Massachusetts Lowell. *Solar Irradiation Database.* [cited 2009 Jan 7]; Available from: http://energy.caeds.eng.uml.edu/fpdb/Irrdata.asp.
18. Renewable Resource Data Centre, *30-Year Average of Monthly Solar Radiation, 1961-1990*, N.R.E. Laboratory, Editor. 2009: Golden, Columbia.
19. F. Jiang and A. Wong, *Study on the Performance of Different Types of PV Modules in Singapore*, in *IEEE: The 7th International Power Engineering Conference.* 2005: Singapore. p. 1-109.

20. T. Markvart, *Chapter 3.3 How Solar Cells Work*, in *Solar Electricity*. 2000, John Wileys & Sons, Inc.: Southampton, UK.
21. B. O'Regan and M. Gratzel, *A low cost, high efficiency solar cell based on dye-sensitized colloidal TiO_2 films.* Nature, 1991. **353**.
22. A.C. Mayer et all, *Polymer Based Solar Cells.* MaterialsToday, 2007. **10**(11).
23. F. Antony; C. Durschner and K-H Remmers, *2.4 PV Modules*, in *Photovoltaics for Professionals: Solar Electric Systems Marketing, Design and Installation.* 2007, Solarpraxis AG: Berlin. p. 57-69.
24. T. Markvart, *Chapter 4.3 The Photovoltaic Generator*, in *Solar Electricity*. 2000, John Wileys & Sons, Inc.: Southampton, UK.
25. F. Jiang, *Investigation of Solar Energy for Photovoltaic Application in Singapore*, in *IPEC: International Power Engineering Conference,*. 2007, Institute of Electrical and Electronics Engineers: Singapore.
26. Lectogic Electrical Services Co. *Solar Electric: Stand-Alone Photovoltaic Systems.* 2008 [cited 2009 June 29]; Available from: http://www.lectogic.co.uk/solar.html.
27. F. Antony; C. Durschner and K-H Remmers, *2.2 PV Module Technology*, in *Photovoltaics for Professionals: Solar Electric Systems Marketing, Design and Installation*. 2007, Solarpraxis AG: Berlin. p. 52.
28. M. A. Green et all, *Solar Cell Efficiency Tables (Version 32).* Progress in Photovoltaics: Research and Application, 2008. **16**: p. 435-440.
29. L. M. Goncalves et all, *Dye Sensitized Solar Cell: A safe bet for the future.* Energy & Environmental Science, 2008. **1**.
30. University of Delaware, *UD-led team sets solar cell record, joins DuPont on $100 million project*, in *UDaily, University of Delaware*. 2007, Office of Communications and Marketing: Delaware.
31. Y. Chiba et all, *Dye-Sensitized Solar Cells with Conversion Efficiency of 11.1%.* Japanese Journal of Applied Physics, 2006. **45**(25).
32. J. Y. Kim et all, *Efficient Tandem Polymer Solar Cells Fabricated by All-Solution Processing.* Science, 2007. **317**(5835).
33. M. C. Beard et all, *Multiple Excition Generation in Colloidal Silicon Nanocrystals.* Nano Letters, 2007. **7**(8): p. 2506-2512.
34. M. A. Green et all, *Solar Cell Efficiency Tables (Version 33).* Progress in Photovoltaics: Research and Application, 2009. **17**: p. 85-94.
35. University of New South Wales, *Highest Silicon Solar Cell Efficiency Ever Reached*, in *ScienceDaily*. 2008: Rockville.
36. J. Zhao; A. Wang and M. A. Green, *19.8% Efficient "honeycomb" textured multicrystalline and 24.4% monocrystalline silicon solar cells.* Applied Physics Letters, 1998. **73**(14): p. 1991-1993.
37. O. Schultz; S. W. Glunz and Willeke GP, *Multicrystalline Silicon Solar Cell Exceeding 20% of Efficiency.* Progress in Photovoltaics: Research and Application, 2004. **12**: p. 553-558.
38. SunPower, *Product Specification -- 300 Solar Panel :Exceptional Efficiency and Performance*, in *http://www.sunpowercorp.com.au/products/commercial_solar_panels.html*, S. Corp., Editor. 2009: Santa Barbara

39. Kyocera Solar. *Product: Specification Sheets*. 2009 [cited 2009 July 12]; Available from: http://www.kyocerasolar.com/products/spec_module.html.
40. [cited 2009 July 12]; Available from: http://www.wholesalesolar.com/solar-panels.html.
41. M. Osborne, *New Product: Mitsubishi Electric boosts multicrystalline cell efficiency to 18.9%*, in *Photovoltaic International*. 2009, Semiconductor Media Limited: London.
42. Mitsubishi Electric. *Product Specifications*. 2009 July 12, 2009; Available from: https://www.mitsubishielectricsolar.com/2009/products/specifications/.
43. C. Honsberg and S. Bowden, *Chapter 4: Solar Cell Operation -- Solar Cell Parameters*, in *Photovoltaic Education Network: PV CDROM*. 2009.
44. T. Markvart, *Chapter 3.4 Silicon Solar Cell Technology*, in *Solar Electricity*. 2000, John Wileys & Sons, Inc.: Southampton, UK.
45. SolarBuzz Consulting. *Solar Module Price Highlights: July 2009*. 2009 [cited 2009 July 17,]; Available from: http://www.solarbuzz.com/Moduleprices.htm.
46. M. A. Green, *Thin Film Solar Cells: review of materials, technologies and commercial status.* Journal of Materials Science : Mater Electron, 2007. **18**: p. S15-S19.
47. United Solar. *Product Specifications: Solar Laminate PVL Series -- Model PVL-68*. 2009 [cited 2009 July 13]; Available from: http://www.uni-solar.com/uploadedFiles/PVL-68-EN.pdf.
48. Kaneka Inc. *Product Specifications: Amorphous Si*. 2009 [cited 2009 July 13]; Available from: http://www.pv.kaneka.co.jp/products/index.html.
49. CSG Solar AG. *Product Specifications: CSG70 to CSG90 Series*. 2009 [cited 2009 July 13]; Available from: http://www.blitzstrom.de/fileadmin/downloads_solar_photovoltaik/BS_CSG_eng.pdf.
50. T. Markvart, *Chapter 3.5 Thin Film Solar Cells*, in *Solar Electricity*. 2000, John Wileys & Sons, Inc.: Southampton, UK.
51. Business Wire, *First Solar Passes $1 Per Watt Industry Milestone: Company Cuts Manufacturing Cost to 98 Cents Per Watt in Fourth Quarter*, in *Business Wire*. 2009: Tempe, Arizona, USA.
52. C. Martin, *First Solar Shares Fall on Reduced Forecast for Sales in 2009*, in *Bloomberg*. 2009, Bloomberg Press: New York.
53. First Solar. *Key Quarterly Financial Data and Supplemental Data*. 2009; Available from: http://media.corporate-ir.net/media_files/irol/20/201491/Q408_supp.pdf.
54. Showa Shell Sekiyu K. K. *Product Specifications: 80W Residential CIS Thin Film Solar Panels*. 2009; Available from: http://www.showashell-solar.co.jp/products/index.html.
55. J. Vidal, *Solar Energy 'Revolution' Brings Green Power Closer*, in *The Guardian,*. 2007: London, UK.
56. N. S. Lewis and G. Crabtree, *Basic Research Needs for Solar Energy Utilization*, U. Department of Energy, Editor. 2005: Washington D. C.
57. C. Honsberg and A. Barnett, *High Efficiency Photovoltaics*, in *UD Energy Institute Syposium*. 2008: Delaware,.
58. National Renewable Energy Laboratory, *NREL Solar Cell Sets World Efficiency Record at 40.8 Percent*. 2008.
59. J. F. Geisz et all, *High-efficiency GaInP/GaAs/InGaAs triple-junction solar cells grown inverted with a metamorphic bottom junction.* Applied Physics Letters, 2007. **91**(2): p. 3502-3503.

60. T. A. Skotheim, *Dye-sensitized Solar Cell*, U.P. Office, Editor. 1978, W, Tupman: the United States.
61. M. K. Nazeeruddin et al, *Conversion of light to electricity by cis-X2bis(2,2'-bipyridyl-4,4'-dicarboxylate)ruthenium(II) charge-transfer sensitizers (X = Cl-, Br-, I-, CN-, and SCN-) on nanocrystalline titanium dioxide electrodes.* Journal of American Chemical Society, 1993. **115**(14).
62. M. K. Nazeeruddin et al, *Combined experimental and DFT-TDDFT computational study of photoelectrochemical cell ruthenium sensitizers.* Journal of American Chemical Society, 2005. **127**(48).
63. Y. Chiba et all, *Dye-Sensitized Solar Cells with Conversion Efficiency of 11.1%.* Japanese Journal of Applied Physics, 2006. **45**(25): p. L638-L640.
64. N. S. Sariciftci; L. Smilowitz; A. J. Heeger and F. Wudl, *Photoinduced Electron Transfer from a Conducting Polymer to Buckminsterfullerene.* Science, 1992. **258**(5087): p. 1474-1476.
65. J. Peet et all, *Efficiency enhancement in low-bandgap polymer solar cells by processing with alkane dithiols.* Nature Material, 2007. **6**: p. 497-500.
66. J. Y. Kim et all, *Efficient Tandem Polymer Solar Cells Fabricated by All-Solution Processing.* Science, 2007. **317**: p. 222-225.
67. European Photovoltaic Industry Association (EPIA), *Global PV Market Outlook Until 2013*. 2008, European Photovoltaic Industry Association: Brussels, Belgium.
68. H. De Moor et all, *R&D for PV Products Generating Clean Electricity*, in *PV NET European Roadmap for PV R&D*, A. Jager-Waldau, Editor. 2004, European Commission: Luxembourg.
69. Interior, D.o.t., *United States Geological Survey*, D.o.t. Interior, Editor. 2009: Washington D. C.
70. Statistics, S.D.o. *Monthly Digest of Statistics Singapore* 2009; Available from: http://www.singstat.gov.sg/pubn/reference.html.
71. Statistics, S.D.o. *Yearbook of Statistics Singapore*. 2008; Available from: http://www.singstat.gov.sg/pubn/reference.html.
72. S. Y. Phang, *The Singapore Model of Housing and The Welfare State*, in *Housing and the New Welfare State: Prospectives from East Asia and Europe*, R. Groves; A. Murie and C. J. Watson, Editor. 2007, Ashgate Publishing, Ltd.: Birmingham, UK. p. 17.
73. Energy Market Authority(EMA) of Singapore, *License Application for Electricity Wholesale (Generation)*, E.M. Authority, Editor. 2009: Singapore.
74. Energy Market Company(EMC) of Singapore. *Market Administration - Registration and Authorisation.* Market Manuals 2009 [cited 2009 July 22]; Available from: http://www.emcsg.com/n393,86.html.
75. Energy Market Authority, *Handbook for Photovoltaic (PV) Systems* Energy Market Authority of Singapore, Editor. 2009: Singapore.
76. SP(Singapore Power) Power Grid, *How to Apply for Electricity Connection*, S.P. Ltd, Editor. 2008, SP PowerGrid Ltd and SP Services Ltd: Singapore.
77. Energy Market Company(EMC) of Singapore. *Prices*. 2009 [cited 2009 July 22]; Available from: http://www.emcsg.com/n390,20.html.
78. Energy market Company(EMC) of Singapore. *Market Rules*. 2009 [cited 2009 July 22]; Available from: http://www.emcsg.com/n916,12.html.

79. Synergyst (thesynergyst.com), *Global Solar Photovoltaic Market Report*. 2008: Mumbai, Maharashtra, India.
80. R. Wiser; G. Barbose and C. Peterman, *Tracking the Sun: The Installed Cost of Photovoltaics in the U.S. from 1998-2007*, L.B.N. Laboratory, Editor. 2009: Berkeley, CA, USA.
81. S. Hegedus and A. Luque, *Status, Trends, Challenges and the Bright Future of Solar Electricity from Photovoltaics*, in *Handbook of Photovoltaic Science and Engineering,*, A. Luque and S. Hegedus, Editor. 2003, John Wiley & Sons, Ltd: Chichester, England. p. 33.
82. P. Lorenz and T. Seitz, *The Economics of Solar Power*, T.S.o.K. Kansas Corporation Commission, United States, Editor. 2009, The State of Kansas Corporation Commission: Topeka, Kansas, United States.
83. W. Shen, *Design of Stand-alone Photovoltaic System at Minimum Cost in Malaysia*, in *3rd IEEE Conference on Industrial Electronics and Applications*. 2008, Institute of Electrical and Electronics Engineers: Singapore. p. 702-705.
84. Navigant Consulting, *A Review of PV Inverter Technology: Cost and Performance Projections*, U.S.D.o. Energy, Editor. 2006, National Renewable Energy Laboratory: Burlington, Massachusetts, United States.
85. W. Bower; S. Gonzalez and M. Ropp, *Photovoltaic (PV) Inverter and BOS Development &Testing* U.S.D.o.E. Sandia National Laboratories, Editor. 2007, Sandia National Laboratories: Denver, Colorado, United States.
86. IMS Research, *the world market for photovoltaic (pv) inverters*. 2009: Austin, Texas, USA.
87. NREL, *Solar Advisor Model*, National Renewable Energy Laboratory, Editor. 2008: Golden,.
88. SolarBuzz Consulting. *All Charge Controller Price Index*. 2009 [cited 2009 July 25]; Available from: http://www.solarbuzz.com/Regulatorprices.htm.
89. Ministry of Trade and Industry (MTI) of Singapore, *National Energy Policy Report: EnergyForGrowth*, M.o.T.a. Industry, Editor. 2009: Singapore. p. 31.
90. Housing Development Board. *Map to Find Location of HDB Carpark*. E-Services 2009 [cited 2009 July 20]; Available from: http://www.hdb.gov.sg/bn22/bn22004p.nsf/SingaporeMap?OpenForm.
91. Housing Development Board, *Flat Type*, in *Virtual Exhibition of HDB Flats*. 2009.
92. Singapore Power(SP) Group. *Electricity Tariff Revision for the Period 1 January to 31 March 2009*. 2008 [cited 2009 10 June]; Available from: http://www.singaporepower.com.sg/publish/PR/Files/Approve/PR4_12422.html.
93. Energy Market Company(EMC) of Singapore, *Price View: Wholesale Electricity Price from 15 Jun 2009 to 12 Jul 2009*, E.M.C.E.o. Singapore, Editor. 2009: Singapore.
94. Economic Development Board(EDB) of Singapore, *Factsheets: Solar Capability Scheme (SCS)* E.D. Board(EDB), Editor. 2008: Singapore.
95. Tuas. *Environment*. 2009 Jan 14, 2009]; Available from: http://tuaspower.com.sg/tuas3.asp.
96. Senoko. *Care for the Environment*. 2009 Jan 11, 2009; Available from: http://senokopower.com.sg/pdf/Care_Environment.pdf.
97. Point Carbon website. *Trading Analystics*. 2009 [cited 2009 July 26]; Available from: http://www.pointcarbon.com/trading/.

98. Olso. *Carbon Trading Price Rise Predicted.* 2009 [cited 2009 July 16]; Available from: http://www.renewableenergyworld.com/rea/news/article/2009/06/carbon-trading-price-rise-predicted.
99. EMA. *Maximum Monthly Peak System Demand.* 2008 [cited 2009 Jan 19]; Available from: http://www.ema.gov.sg/FILES/maximum_mthly_peak_system_demand.pdf.
100. LTA, *Singapore Land Transport Statistics in Brief 2008.* 2008.
101. The Association for the Study of Peak Oil and Gas, *ASPO Newsletter: The General Depletion Picture*, in *ASPO Newsletter 61*. Jan 2006: Cork, Ireland.
102. LTA, *Transcending Travel: a Macro View.* 2008. p. 5.
103. Montes, M.J., A. Abanades, and J.M. Martinez-Val, *Performance of a direct steam generation solar thermal power plant for electricity production as a function of the solar multiple.* Solar Energy, 2009. **83**(5): p. 679-689.
104. Land Transport Authority, *Annual Vehicle Statistics.* 2008, Land Transport Authority.
105. Cnet News. *Better Place Plugs in Battery Swapping Station.* 2009 [cited 2009, July 19]; Available from: http://news.cnet.com/8301-11128_3-10239641-54.html.
106. *Uniform Singapore energy price and demand forecast.* 2009, Energy Market Company.
107. *Transcending Travel: A Macro View.* 2008, Land Transport Authority.
108. Ochieng, R.M. and F.N. Onyango, *A new type of solar concentrator employing a cone-cylinder combination.* International Journal of Global Energy Issues, 2009. **31**(2): p. 169-182.
109. *2008 Toyota (Crown) Comfort [Hong Kong taxi].* Available from: http://www.flickr.com/photos/stephenwoolverton/2623571973.
110. Energy Information Administration. *Singapore Conventional Premium Gasoline Spot Price FOB (Cents per Gallon)* 2009 [cited 2009, July 23]; Available from: http://tonto.eia.doe.gov/dnav/pet/hist/rp15sin5d.htm.
111. EMC. *Market Data - Prices.* 2009 [cited 2009 July 25]; Available from: http://www.emcsg.com/default.aspx?id=3152&area=20&pcid=1224&startPriceDay=1&startPriceMonth=8&startPriceYear=2009&endPriceDay=31&endPriceMonth=8&endPriceYear=2009&Submit=Go.
112. Kramer, F., *Commercializing Plug-In Hybrids.* 2009, The California Cars Initiative.
113. Cheng, K. and D. Han, *Experimental study of the thermal performance of the receiver with the dish type concentrator system.* Taiyangneng Xuebao/Acta Energiae Solaris Sinica, 2009. **30**(1): p. 64-68.
114. Singapore Street Directory. *IMM Building.* 2009 [cited 2009 July 25]; Available from: http://www.streetdirectory.com/stock_images/travel/normal_show/11867391760055/121980/imm_building_main_view/.
115. IMM. *IMM Shopping Mall.* 2009 [cited 2009 July 25]; Available from: http://www.imm.sg/abt_mall.htm.
116. *Energy Storage System Performance Goals for Power-Assist Hybrid Electric Vehicles.* 2002, US Advanced Battery Consortium.
117. MTI. *Energy for Growth - National Energy Policy Report.* 2007.
118. Housing Development Board(HDB) of Singapore, *HDB Annual Report 2007/2008: Cumulative Achievements*, H.D. Board, Editor. 2008: Singapore. p. 57.
119. Land Transport Authority, *Land Transport Statistics in Brief.* 2008: Singapore.
120. Energy Market Authority, *Singapore Electricity Market Rules*, E.M.A.o. Singapore, Editor. 2009: Singapore.

121. Eugene (LowCarbonSG). *Overview of the Energy Situation in Singapore*. 2009 [cited 2009, July 23]; Available from: http://www.lowcarbonsg.com/2009/05/14/overview-of-the-energy-situation-in-singapore/.

Appendix 1[3][4]: Crystalline Si Modules

SUNPOWER

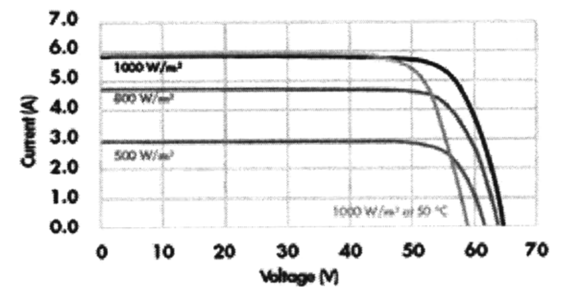
300 SOLAR PANEL

EXCEPTIONAL EFFICIENCY AND PERFORMANCE

Electrical Data		
Measured at Standard Test Conditions (STC): irradiance of 1000/m², air mass 1.5 g, and cell temperature 25° C		
Peak Power (+/−3%)	Pmax	300 W
Rated Voltage	Vmp	54.7 V
Rated Current	Imp	5.49 A
Open Circuit Voltage	Voc	64.0 V
Short Circuit Current	Isc	5.87 A
Maximum System Voltage	IEC	1000 V
Temperature Coefficients		
	Power	−0.38% / °C
	Voltage (Voc)	−176.6 mV/°C
	Current (Isc)	3.5 mA/°C
Series Fuse Rating		15 A
Peak Power per Unit Area		184 W/m²

Mechanical Data	
Solar Cells	96 SunPower all back-contact monocrystalline
Front Glass	4.0 mm (5/32 in) tempered
Junction Box	IP-65 rated with 3 bypass diodes
Output Cables	900 mm length cables / Multi-Contact connectors
Frame	Anodized aluminum alloy type 6063
Weight	24 kg, 53 lbs

IV Curve



Current/voltage characteristics with dependence on irradiance and module temperature.

Tested Operating Conditions	
Temperature	−40° C to +85° C (−40° F to +185° F)
Max load	240 kg/m² (2400 Pascals) front and back
Impact Resistance	Hail – 25mm (1 in) at 23 m/s (52 mph)

Warranty and Certifications	
Warranty	25 year limited power warranty
	10 year limited product warranty
Certifications	IEC 61215, Safety tested IEC 61730

■ Specifications

■ Electrical Performance under Standard Test Conditions (*STC)	
Maximum Power (Pmax)	200W (+10%/−5%)
Maximum Power Voltage (Vmpp)	26.3V
Maximum Power Current (Impp)	7.61A
Open Circuit Voltage (Voc)	32.9V
Short Circuit Current (Isc)	8.21A
Max System Voltage	600V
Temperature Coefficient of Voc	-1.23×10^{-1} V/℃
Temperature Coefficient of Isc	3.18×10^{-3} A/℃

*STC: Irradiance 1000W/m², AM1.5 spectrum, module temperature 25℃

■ Electrical Performance at 800W/m², NOCT, AM1.5	
Maximum Power (Pmax)	142W
Maximum Power Voltage (Vmpp)	23.2V
Maximum Power Current (Impp)	6.13A
Open Circuit Voltage (Voc)	29.9V
Short Circuit Current (Isc)	6.62A

NOCT (Nominal Operating Cell Temperature): 47℃

■ Cells	
Number per Module	54

■ Module Characteristics	
Length × Width × Depth	1425mm(56.2in)×990mm(39.0in)×36mm(1.4in)
Weight	18.5kg(40.7lbs.)
Cable	(+)720mm(28.3in),(-)1800mm(70.9in)

■ Junction Box Characteristics	
Length × Width × Depth	113.6mm(4.5in)×76mm(3.0in)×9mm(0.4in)
IP Code	IP65

■ Reduction of Efficiency under Low Irradiance	
Reduction	7.8%

Reduction of efficiency from an irradiance of 1000W/m² to 200W/m² (module temperature 25℃)

Please contact our office for further information

KYOCERA

[3] http://www.sunpower.com/
[4] http://www.kyocerasolar.com/

Appendix 2[5,6,7]: Si based Thin Film Modules

Electrical Specifications

STC

(Standard Test Conditions)

(1000 W/m^2, AM 1.5, 25 °C Cell Temperature)

Maximum Power (P_{max}): 68 W
Voltage at Pmax (V_{mp}): 16.5 V
Current at Pmax (I_{mp}): 4.13 A
Short-circuit Current (I_{sc}): 5.1 A
Open-circuit Voltage (V_{oc}): 23.1 V
Maximum Series Fuse Rating: 8 A

NOCT

(Nominal Operating Cell Temperature)

(800 W/m^2, AM 1.5, 1 m/sec. wind)

Maximum Power (P_{max}): 53 W
Voltage at Pmax (V_{mp}): 15.4 V
Current at Pmax (I_{mp}): 3.42 A
Short-circuit Current (I_{sc}): 4.1 A
Open-circuit Voltage (V_{oc}): 21.1 V
NOCT: 46 °C

Temperature Coefficients

(at AM 1.5, 1000 W/m^2 irradiance)

Temperature Coefficient (TC) of I_{sc}: 0.001/°K(0.10%/°C)
Temperature Coefficient (TC) of V_{oc}: -0.0038/°K (-0.38%/°C)
Temperature Coefficient (TC) of P_{max}: 0.0021/°K (-0.21%/°C)
Temperature Coefficient (TC) of I_{mp}: 0.001/°K (0.10%/°C)
Temperature Coefficient (TC) of V_{mp}: -0.0031/°K (-0.31%/°C)

y = yreference • [1 + TC • (T- Treference)]

UNI-SOLAR®

[5] http://www.pv.kaneka.co.jp/products/index.html
[6] http://www.uni-solar.com/
[7] http://www.csgsolar.com/

KANEKA G - EA060

Elektrické údaje			
Jmenovitý výkon	P_n	60	W_p
Napětí v bodě max. výkonu	U_{mpp}	67	V
Proud v bodě max. výkonu	I_{mpp}	0,9	A
Napětí naprázdno	U_o	92	V
Zkratový proud	I_{sc}	1,19	A
Účinnost modu (plocha 0,95 m²)	η_m	6,3	%

Teplotní součinitelé		
Proud (I_{sc})	0,075	%/K
Napětí (U_o)	-280	mV/K
Výkon (P_n)	-0,23	%/K

Limity	
Systémové napětí	530 V_{DC}

El. údaje měřeny při standardních testovacích podmínkách (STC): intenzita záření 1000 W/m², teplota 25 °C, spektrum AM 1,5

Mechanické údaje			
Technologie	Amorfní křemík	Tolerance výkonu	+10 % ...-5%
Rozměr (v x š x h)	960 X 990 X 40 mm	Ochranné diody	Integrovány
Váha	13,7 kg	Připojení	Kabely s konektory MC3

csgsolar taking the next step

Electrical Specifications

All Numbers obtained at STC: Imission 1000 W/m² with spectrum AM 1.5 at a cell temperature of 25 °C.

Blitzstrom		Tolerance	CSG-70	CSG-75	CSG-80	CSG-85	CSG-90
Nominal Power	P_{MPP}	-0% /+5%	70 Wp	75 Wp	80 Wp	85 Wp	90 Wp
Voltage at P_{MPP}	U_{MPP}	-5% /+5%	56 V	57 V	59 V	61 V	63 V
Current at P_{MPP}	I_{MPP}	-5% /+5%	1.32 A	1.34 A	1.37 A	1.41 A	1.45 A
Open Circuit Voltage	U_{OC}	-5% /+5%	78 V	79 V	80 V	81 V	82 V
Short Circuit Current	I_{SC}	-5% /+5%	1.56 A	1.57 A	1.59 A	1.62 A	1.65 A

Dimensions and Weight

Dimensions (Tolerance ±1.5mm)	1253 mm x 1103 mm = 1.38m²
Frame height (Tolerance ±1.5mm)	41 mm
Mechanical Weight	14.5 kg

Key Features

Number of cells	175, monolithically linked
Cell type	Crystalline Silicon on Glass (CSG)
Front cover	Borosilicate glass (3.3mm)
Encapsulant	EVA (Ethylene Vinyl Acetate)
Backsheet	Tedlar-Polyester (TPE)
Frame	Silver anodized aluminium
Output terminals	Solar cables with MC® connectors (MC-4), IP65
Bypass diode	1

Temperature Coefficients

Temperature Coefficient of P_{MPP}	$T_K (P_n)$	-0.45% to -0.6% /°C *
Temperature Coefficient of U_{OC}	$T_K (U_{OC})$	- 390 mV / °C
Temperature Coefficient of I_{SC}	$T_K (I_{SC})$	+ 1.5 mA / °C
NOCT (Nominal Operating Cell Temperature)		41°C

(* according to technical progress)

Operational Limits

Maximum system voltage	1000 V_{DC}
Operating temperature	-40°C to +90°C
Tested wind resistance	130 km/h
Hail resistance	25mm at 83 km/h

Certifications

The pv modules Blitzstrom CSG 70 to CSG 90 are manufactured by CSG Solar AG, Germany. IEC 61215, IEC 61646, IEC 61730 and TÜV Safety Class II certification will be issued in 2007.

Appendix 3[8][9]: II-VII Thin Film Modules

First Solar FS Series 2 PV Module

ELECTRICAL SPECIFICATIONS

MODEL NUMBERS AND RATINGS AT STC[1]*

Nominal Values		FS-270	FS-272	FS-275	FS-277
Nominal Power(+/-5%)	P_{MPP}(W)	70	72.5	75	77.5
Voltage at P_{MAX}	V_{MPP}(V)	65.5	66.6	68.2	69.9
Current at P_{MAX}	I_{MPP}(A)	1.07	1.09	1.10	1.11
Open Circuit Voltage	V_{OC}(V)	88.0	88.7	89.6	90.5
Short Circuit Current	I_{SC}(A)	1.23	1.23	1.23	1.22
Maximum System Voltage	V_{SYS}(V)	1000 (600 UL[2])			
Temperature Coefficient of P_{MPP}	$T_K(P_{MPP})$	-0.25%/°c			
Temperature Coefficient of V_{OC}, high temp (>25°C)	$T_K(V_{OC,\ high\ temp})$	-0.25%/°c			
Temperature Coefficient of V_{OC}, low temp (-40°C to +25°C)	$T_K(V_{OC,\ low\ temp})$	-0.20%/°c			
Temperature Coefficient of I_{SC}	$T_K(I_{SC})$	+0.04%/°c			
Limiting Reverse Current[3]	I_R(A)	2			
Maximum Source Circuit Fuse	I_{CF}(A)	10 (2 UL/IEC61730[4])			

MODEL NUMBERS AND RATINGS AT 800W/m², 45°C, AM 1.5*

Nominal Values		FS-270	FS-272	FS-275	FS-277
Nominal Power(+/-5%)	P_{MPP}(W)	52.6	54.4	56.3	58.1
Voltage at P_{MAX}	V_{MPP}(V)	61.4	62.5	63.9	65.4
Current at P_{MAX}	I_{MPP}(A)	0.86	0.87	0.88	0.89
Open Circuit Voltage	V_{OC}(V)	81.8	82.5	83.3	84.2
Short Circuit Current	I_{SC}(A)	1.01	1.01	1.01	1.00

MECHANICAL DESCRIPTION

Length	1200mm	Thickness	6.8mm
Width	600mm	Area	0.72m²
Weight	12kg	Leadwire	3.2mm², 610mm
Connectors	Solarline 1 type connector		
Bypass Diode	None		
Cell Type	CdS/CdTe semiconductor, 116 active cells		
Frame Material	None		
Cover Type	3.2mm heat strengthened front glass laminated to 3.2mm tempered back glass		
Encapsulation	Laminate material with edge seal		

[8] www.firstsolar.com/
[9] www.showa-shell.co.jp/english/index.html

Showa Shell Sekiyu K.K

型式	SC80-RT-A（傾斜屋根用）	SC80-A（陸屋根用）	SC75-RT-A（傾斜屋根用）	SC75-A（陸屋根用）	SC70-RT-A（傾斜屋根用）	SC70-A（陸屋根用）
発電素子	CIS（薄膜系）					
公称最大出力[※1](Pm)	80W		75W		70W	
公称最大出力動作電圧(VPm)	41.0V		40.5V		37.6V	
公称最大出力動作電流(Ipm)	1.95A		1.85A			
公称開放電圧(Voc)	56.5V		55.5V		54.0V	
公称短絡電流(Isc)	2.26A		2.20A			
公称質量	11.5kg	12.4kg	11.5kg	12.4kg	11.5kg	12.4kg
外形寸法(mm, W×L×D)[※2]	671×1,235×23(35)	641×1,235×35	671×1,235×23(35)	641×1,235×35	671×1,235×23(35)	641×1,235×35
推奨直列数	3～6 直列[※3]				4～6 直列	
推奨直列数（自動昇圧ユニット使用時）	2～5 直列				2～5 直列	